

Comparative analysis of radon, thoron and thoron progeny concentration measurements

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This study examined correlations between radon, thoron and thoron progeny concentrations based on surveys conducted in several different countries. For this purpose, passive detectors developed or modified by the National Institute of Radiological Sciences (NIRS) were used. Radon and thoron concentrations were measured using passive discriminative radon-thoron detectors. Thoron progeny measurements were conducted using the NIRS-modified detector, originally developed by Zhuo and Iida. Weak correlations were found between radon and thoron as well as between thoron and thoron progeny. The statistical evaluation showed that attention should be paid to the thoron equilibrium factor for calculation of thoron progeny concentrations based on thoron measurements. In addition, this evaluation indicated that radon, thoron and thoron progeny were independent parameters, so it would be difficult to estimate the concentration of one from those of the others.

Keywords: radon; thoron; thoron progeny; thoron equilibrium factor

INTRODUCTION

Inhalation of radon (Rn) and its short-lived decay products, as well as of the thoron (Tn) series, accounts for about half of the effective dose from natural radiation sources. In the past, Rn studies were more common than those of Tn, but recent studies in Serbian [1–3], Chinese [4, 5], Indian [6] Canadian [7–9], Japanese [10], Korean [11, 12], Hungarian [13], Slovenian [14], Irish [15, 16] and USA [17] dwellings have shown that Tn can be a significant contributor to the radiation exposure. The contributions of Rn and Tn and its progeny (TnP) to radiation exposure are quite different. The decay half life of Rn is 3.82 d, which is long enough for its transfer from a source (mainly soil) through cracks and gaps

into indoor spaces. Several parameters, such as dwelling type, ventilation rate and construction materials, influence the Rn concentration in dwellings. Due to its long half life, Rn is usually well-mixed in room air. On the other hand, due to the relatively short half life of Tn (55.6 s), its presence is highly inhomogeneous in room air and is strongly dependent on distance from the source [18–21]. Also, Tn can interfere with the detection of Rn in detectors that lack diffusion barrier discrimination and thus allow rapid gas entry into the sensitive volume [22]. For a rough estimation of lung dose using the equation given by UNSCEAR [23], several important components are required, such as the equilibrium equivalent concentration (*EEC*), the equilibrium factor (*F*) and gas concentration (*C*).

Since direct measurements of the concentration of all short-lived Rn and Tn decay products are difficult and limited, the *EEC* is estimated from considerations of equilibrium (or disequilibrium) between Rn and Tn and their decay products, and is expressed by the equation:

$$EEC_c = F_x \times C_x,$$

where x is Rn or Tn. Several groups have reported the Rn equilibrium factor to be within the range 0.3–0.6 [24–27], which is close to the typical value of 0.4 adopted by UNSCEAR.

On the other hand, simultaneous long-term measurements of Tn and its progeny have rarely been conducted, and there is a shortage of data on *EEC* for Tn [4, 26–32]. As a result, the progeny concentration is usually estimated by multiplying the Tn concentration by a typical equilibrium factor for Tn ($F_{Tn} = 0.02$), which has also been provided by the UNSCEAR Report.

In the present study, data from six Rn and Tn surveys in China (S1 and S2), Ireland (S3) and Korea (S4, S5, and S6) were analyzed. The Chinese surveys were conducted in Gansu Province by the National Institute of Radiological Science (NIRS, Japan) in cooperation with National Institute for Radiological Protection (NIRP, China) and Kagoshima University (Japan) [4]. A previous study carried out by the Chinese Laboratory of Industrial Hygiene and the US National Cancer Institute showed an increased lung cancer risk due to high residential Rn levels. Other Chinese surveys provided by Tokonami *et al.* [33] and Sun *et al.* [34] found areas with high levels of Tn. Simultaneous measurements of indoor Rn, Tn and airborne TnP were made in Ireland for the evaluation of long-term exposures in dwellings [16]. The Korean studies were designed as nationwide surveys for Rn, Tn and TnP to provide annual averages of them and to estimate the effective dose for the general public [35].

All of these surveys were carried out using both the passive Rn and Tn detectors and the TnP monitor developed by the NIRS, and data were examined to investigate any relationship between Rn and Tn; between Rn and TnP; and between Tn and TnP. In addition, the problem of evaluation of the Tn equilibrium factor was considered.

MATERIALS AND METHODS

Rn and Tn measurements

For simultaneous measurements of Rn and Tn, passive integrated Rn–Tn detectors (commercially sold as RADOPOT or RADUET) were used [36–37]. These detectors were developed and evaluated at NIRS. Quality assurance of the detectors was checked by participation in international intercomparisons of passive Rn and Tn detectors; the

difference between the reference value and the registered value did not exceed 20% [38–40].

The working principle for both detectors is the same. A detector consists of two diffusion chambers with different air exchange rates. The chamber with the low air exchange rate (LER) is for Rn registration while the high air exchange rate (HER) chamber is for Tn and Rn registration. The Rn gas in the air diffuses to the LER chamber through a very narrow invisible gap, while Tn diffuses through evenly distributed holes made on the HER chamber wall. The differences between RADOPOT and RADUET detectors are mainly: the inner volume of each chamber; the number and diameter of holes; the covering material for the holes of the HER chamber wall; and the materials from which the detectors are made. The lower limit of detection (LLD) is calculated on the basis of an ISO Guideline [41]. The LLD depends on the concentration of both gases and on the exposure period. For example, when a Rn concentration of 15 Bq m⁻³ and a Tn concentration of 15 Bq m⁻³ are given with a measurement period of 90 days, the detection limits are estimated to be 5 Bq m⁻³ and 7 Bq m⁻³, respectively.

TnP measurement

For the measurement of TnP the detector developed by Zhuo and Iida was used [42]. In the first version of the detector (Fig. 1a) only one CR-39 chip was used. The modified version by NIRS (Fig. 1b), used for these surveys, consists of two or four chips because a larger number of CR-39 chips can achieve better statistics and lower measurement uncertainty. CR-39 chips are covered with an aluminium-vaporized Mylar film of 71-mm air-equivalent thickness. The thickness of the Mylar film allows the detection of only the 8.78 MeV alpha particles emitted from ²¹²Po. The LLD of the modified detector was estimated using the Currie formula [43] to be 0.005 Bq m⁻³ for an exposure period of 90 days. Based on a laboratory calibration of this TnP monitor, the airborne concentration of the Tn decay product ²¹²Pb in the air was determined and expressed as Bq m⁻³ equilibrium equivalent thoron concentration (EETC).

Background and calibration

The background measurements were done using non-exposed detectors, hence registered counts were subtracted from total counts obtained using an exposed detector. In addition, for each series of CR-39 chips a new calibration factor was determined using NIRS Rn and Tn chambers.

The fluctuation of background and efficiency were taken into consideration for estimating Rn, Tn and Tn progeny concentrations [44], and background and efficiency were estimated for each series (product lot) of CR39. The background and efficiency were assumed to be similar within each series (1000 chips of CR39). Even if the background and/or efficiency change from lot to lot, this won't

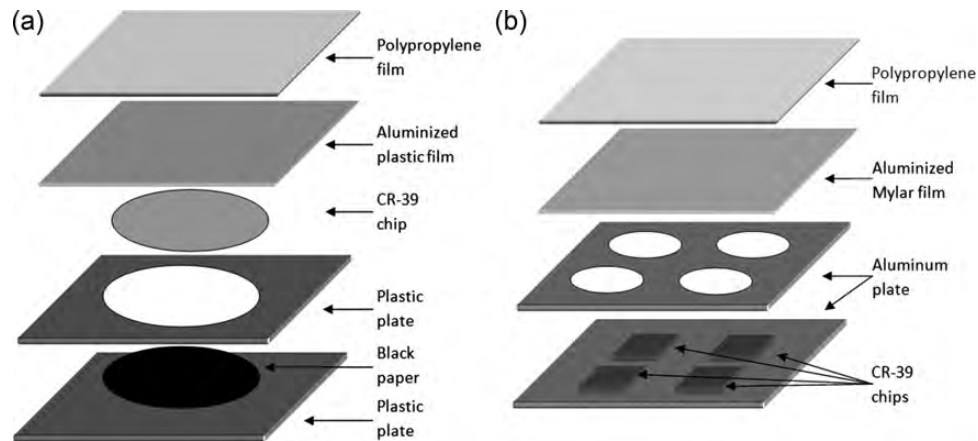


Fig 1. Thoron progeny monitors: (a) developed by Zhuo and Iida [41] and (b) modified by NIRS and used in surveys.

significantly affect the accuracy of estimation. The fluctuation of calibration factors (from 2004) ranges from 0.0088–0.0245 and 0.0049–0.0198 ($\pm 3\text{--}5\%$) tracks $\text{mm}^{-2} \text{ kBq}^{-1} \text{ h}^{-1} \text{ m}^3$ for Rn and Tn, respectively, whereas background fluctuation (from 2004) ranges from 0.08–0.60 tracks mm^{-2} .

Software

Statistical evaluations of the data were performed by R-language packages [45–46]. Normality of distributions was checked by Jarque–Bera (J–B) and d’Agostino (d’A) tests. The statistical hypothesis for the Tn equilibrium factor $F_{Tn} = 0.02$ (null hypothesis—recommended value by UNSCEAR) was checked by the Student’s t-test if results were normally distributed (based on results given by J–B and d’A tests), whereas the Wilcoxon signed-rank test was used if the results could not be assumed to have a normal distribution. In addition, for quantification of the statistical dependence between any two variables (Rn–Tn, Rn–TnP and Tn–TnP) the linear regression model was applied. The number of classes for histograms was made by the Freedman–Diaconis method based on the inter-quartile range [47]. Moreover, data below LLD were excluded from consideration.

Outliers/hot-spots

Datasets of spatial environmental variables are often found to be approximately log-normally distributed. For geochemical variables the phenomenon is well known, and a lot of literature exists regarding this [48]. In addition, the observation of approximate log-normality is abundant for Rn concentration data, thus the term ‘log-normal mysticism’ has been coined [49], requiring further studies. Considering this situation, we believe that most of the outliers/hot-spots identified by our analysis resulted from ‘anomalous’ sampling procedures: for indoor Rn/Tn measurements, apart

from measurement errors and ‘genuinely’ statistical outliers, particular features of the construction of the building, the distance from the wall at which Rn/Tn was measured, behaviour of occupants, environmental conditions, etc. may have led to overestimation of the Rn/Tn concentration. However, the analysis of the nature of anomalies is not within the scope of this study.

In order to identifying the outliers/hot-spots in a survey, the following steps were executed: (i) perform the J–B and d’A tests; (ii) if the P value < 0.05 the highest data was removed, then do the J–B and d’A tests again; and (iii) steps (i) and (ii) were repeated as long as results of the J–B and d’A tests were below the P values.

RESULTS AND DISCUSSION

Results of indoor Rn, Tn and TnP concentration measurements from the six surveys are summarized in Table 1 and shown as box plots in Figs 2a–4a.

All of the surveys were focused on characterizing Tn and TnP levels, and were analyzed to gauge the interference that Tn may cause in typical Rn measurements performed for home risk assessment. For calculation purposes, only raw data with triple results (Rn, Tn and TnP) obtained simultaneously were considered. Data from the different surveys were not merged for analysis due to different detector mounting places. In surveys S1 and S2, RADOPOT detectors were placed at a distance from the wall/ceiling (range, 5–30 cm), whereas for surveys S3–S6 RADUET detectors were mounted on the wall or another suitable surface in the living room. As mentioned earlier, the Tn concentration strongly depends on the distance from the wall. Therefore, if the detector is mounted directly on a wall, it gives an accurate determination of TnP in the room and an indication of the maximum Tn concentration. Furthermore, if the detector distance from the wall is more

Table 1. Results of measurements: original and outlier evaluated data

		Original data						Outlier evaluated data					
		S1	S2	S3	S4	S5	S6	S2m	S3m	S4m	S5m	S6m	
Rn (Bq m ⁻³)	N	104	104	347	387	410	396	89	331	356	402	387	
	Mean	97	81	75	65	68	50	78	75	49	56	42	
	Stdev	58	40	78	67	157	90	36	80	34	56	34	
	Median	76	75	50	39	41	33	70	49	37	40	32	
	GM ^{a,b}	82	72	51	–	–	–	70	52	40	41	34	
	Min.	16	22	4	4	5	5	22	4	4	5	5	
	Max.	303	248	767	468	2841	1543	200	767	148	476	283	
	Skew ^c	1.18	1.50	3.66	2.83	14.03	12.31	1.10	3.63	1.19	3.41	2.91	
	Kurt ^d	0.93	2.99	22.22	10.05	235.03	193.45	1.37	21.59	0.50	16.16	12.33	
Tn (Bq m ⁻³)	Mean	298	432	25	60	73	44	375	26	52	60	38	
	Stdev	265	437	25	121	136	74	346	24	70	70	49	
	Median	206	258	18	34	38	29	246	19	32	38	27	
	GM	214	–	18	–	–	–	278	19	32	40	25	
	Min.	19	47	3	3	3	3	47	3	3	3	3	
	Max.	1200	1922	189	1996	1829	797	1643	189	697	563	515	
	Skew	1.83	2	3.11	11.29	7.55	6.12	2.11	3.10	4.80	3.47	5.40	
	Kurt	2.73	3.01	13.36	167.33	78.95	45.92	3.94	13.31	31.94	15.35	38.55	
	TnP (Bq m ⁻³) EETC	Mean	3.12	2.13	0.46	0.96	1.12	0.78	2.10	0.42	0.96	1.11	0.73
Stdev		1.31	1.03	0.43	0.93	1.19	1.20	0.80	0.29	0.93	1.06	0.91	
Median		2.98	2.04	0.35	0.67	0.79	0.45	2.06	0.35	0.69	0.79	0.43	
GM		2.85	1.86	–	–	0.82	0.44	1.94	0.34	0.36	0.81	0.44	
Min.		0.98	0.24	0.01	0.03	0.06	0.02	0.60	0.03	0.03	0.06	0.02	
Max.		7.23	5.17	3.3	8.84	7.58	16.45	3.96	1.80	8.84	7.58	6.46	
Skew		0.75	0.55	3.35	3.16	3.1	6.86	0.15	1.77	3.22	3.02	3.09	
Kurt		0.40	0.02	15.37	16.40	12.57	74.52	-0.81	4.26	17.12	12.32	11.66	
F _{Tn}		Mean	0.019	0.008	0.035	0.038	0.035	0.034	0.009	0.032	0.040	0.035	0.035
	Stdev	0.018	0.006	0.05	0.052	0.043	0.055	0.006	0.047	0.053	0.044	0.05	
	Median	0.014	0.008	0.018	0.021	0.021	0.017	0.008	0.018	0.022	0.021	0.018	
	GM	0.013	0.006	0.018	–	–	0.017	0.007	0.018	0.021	0.020	0.017	
	Min.	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	<0.001	<0.001	0.001	
	Max.	0.156	0.037	0.5	0.43	0.332	0.573	0.037	0.500	0.430	0.332	0.573	
	Skew	2.54	1.45	4.05	3.39	3.33	5.09	1.72	4.77	3.29	3.31	5.05	
	Kurt	8.36	3.79	23.26	15.53	14.62	37.38	5.45	34.42	14.55	14.44	36.77	

Tn/Rn ratio	Mean	4.33	6.46	0.49	1.38	1.44	1.36	6.17	0.49	1.43	1.38	1.16
	Stdev	4.91	6.94	0.42	2.31	1.56	4.12	6.86	0.41	2.26	1.40	1.35
	Median	2.34	3.79	0.37	0.77	0.97	0.77	3.56	0.38	0.84	0.97	0.78
	GM	2.61	4.2	0.36	-	0.98	-	3.97	0.36	0.82	0.96	0.74
	Min.	0.23	0.77	0.04	0.03	0.05	0.03	0.77	0.04	0.05	0.05	0.03
	Max.	23.56	38.15	3.05	22.75	13.84	78.25	38.15	3.05	22.75	12.43	14.35
	Skew	2.14	2.07	2.4	5.33	3.68	16.56	2.24	2.23	5.40	3.34	4.04
	Kurt	4.71	4.36	8.40	35.64	20.42	303.70	5.36	7.38	37.51	18.03	24.94

^aGeometric mean; ^bwhen neither normal nor lognormal distributions are appropriate only the mean and median values are given; ^cskewness; ^dkurtosis.

than several centimetres the Tn concentration measured can be assumed to be representative of the room.

The range of averages of indoor Rn, Tn and TnP are 50–97 Bq m⁻³, 25–432 Bq m⁻³ and 0.46–3.12 Bq m⁻³ (EETC), respectively.

In the Chinese surveys (S1 and S2), detectors were suspended from the ceiling in the centre of each cave dwelling (range, 5–30 cm), while they were hung on walls for other surveys. The cave dwelling is a particular form of earth shelter dwelling common in the Loess Plateau in China's north. It consists of one room with a single entrance and two windows at the front side. The length is 8–10 m with a width of 3–3.5 m and a height of 3–3.5 m. The cave dwelling is equipped with a traditional bed formed from a loess cube, which is called Kang in Chinese. Regardless of the placement of detectors with some distance from the ceiling and walls (possible source of Tn) in Chinese surveys, the averages of Tn concentration are generally higher. This could be because the cave dwellings were mainly made from the loess without wall coverings and walls (ceilings) are strong sources of Tn. In other surveys, the investigated houses were made from typical building materials with painted walls, and consequently the soil under the houses could be considered the main source of Tn.

Because the average and median values were different in all cases, the skewness for measuring the asymmetry of the distributions was calculated and the results are shown in Table 1. All original (S1–S6) cases show positive skewness (the right tail is longer). This means that values are concentrated mainly on the left side and high values of the right side disturb (increase) the average value. These high values can be recognized as potential outliers/hot-spots and analyzed later.

The J–B and d'A normality tests (Table 2) show that some of the distributions of original data are log-normal at the 0.05 significance level.

The ranges of skewness for S3–S6 Tn measurements are greater than for S1 and S2, however the average values of the concentrations are lower. The difference can be explained by the mounting place of the detectors (for S3–S6 close to the wall, and for S1 and S2 at a distance from the wall), therefore S3–S6 detectors could register close to the maximum Tn concentrations in the rooms. This indicates that special attention must be paid to the location of the detector if a single device is to be used for further evaluation and dose estimation.

In most cases if the survey is conducted within an area up to a few tens of kilometre radius, indoor Rn concentration has a high probability of being log-normally distributed [47]. Based on this assumption a simple method using normality tests has been implemented, which filters outliers from a data population that is known to be (approximately) log-normally distributed.

All the surveys considered in this paper were carried out locally within the maximum 30 km radius, but only a few

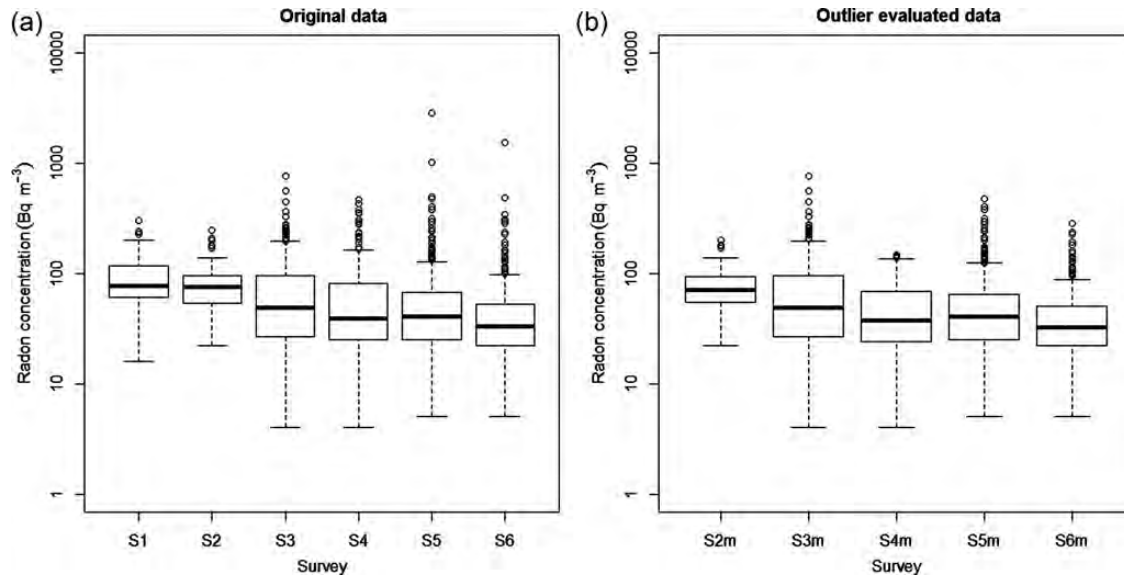


Fig 2. Box plot of radon concentration results: (a) original data (b) outlier evaluated data.

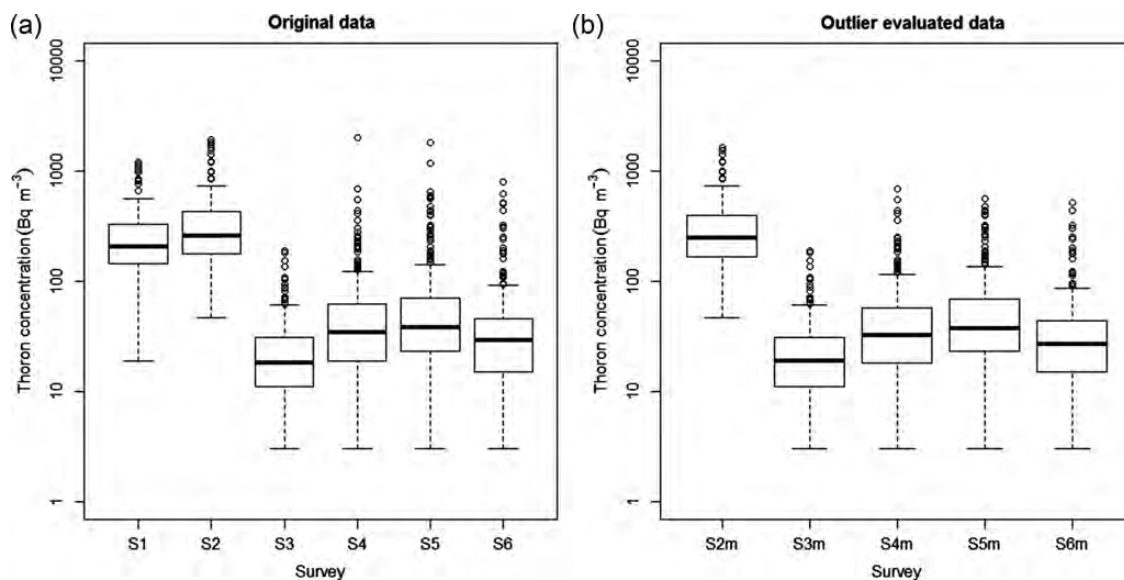


Fig 3. Box plot of thoron concentration results: (a) original data and (b) outlier evaluated data.

distributions of Rn, Tn and TnP passed normality tests (Table 2). One of the reasons for failing the tests is because these surveys were investigated using a single set of detectors (Rn–Tn–TnP) therefore some of results may be inconsistent with other observations in the data population and clearly visible in the Q-Q plots and histograms. Possible outliers are enclosed by ovals in Figs 5a–7a. Other potential sources of error, such as environmental parameters (e.g. pressure and temperature gradients) and ventilation rate, were not analyzed in this paper. Therefore, if the original data did not pass the normality tests, the outlier evaluation to find outliers (or anomalies or hot spots) was executed, i.

e. removal of the maximum values was stopped if the normality tests (J–B and d'A) were passed. The modified results (excluding S1) are denoted as S2m for the S2 survey, ... S6m for the S6 survey, and are listed in Table 1 and presented as box plots in Figs 2b–4b. Because Rn, Tn and TnP for the S1 survey passed the normality tests, no outlier evaluation for this series was performed.

It should be noticed that after outlier evaluation all data for Rn, Tn and TnP concentrations showed log-normal distributions (Table 2 and Figs 5b–7b).

Because one of the most important values for dose calculation is the TnP concentration, the linear dependency

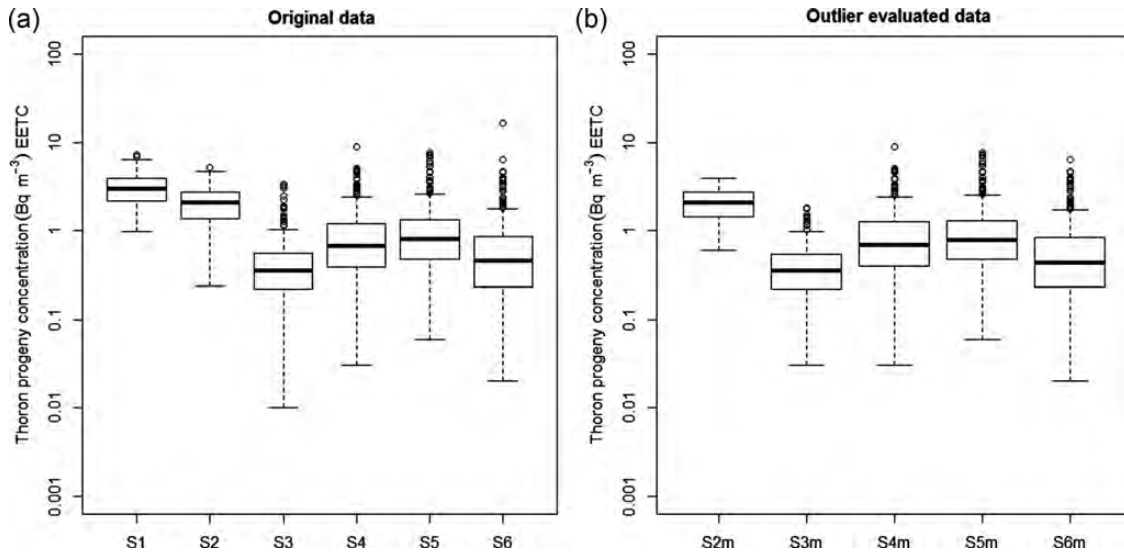


Fig 4. Box plot of thoron progeny concentration results: (a) original data and (b) outlier evaluated data.

Table 2. Jarque–Bera (J–B) and d’Agostino (d’A) normality tests results

Survey	Original data						Outlier evaluated data							
	S1	S2	S3	S4	S5	S6	S2m	S3m	S4m	S5m	S6m			
Parameter	J–B	d’A	J–B	d’A	J–B	d’A	J–B	d’A	J–B	d’A	J–B	d’A	J–B	d’A
Ln(Rn)	O ^a / O	O / O	O / O	- / -	- / -	- / -	O / O	O / O	O / O	O / O	O / O	O / O	O / O	O / O
Ln(Tn)	O / O	- / -	O / O	- / -	- / -	- / -	O / O	O / O	O / O	O / O	O / O	O / O	O / O	O / O
Ln(TnP)	O / O	- / -	- / -	O / O	O / O	O / O	O / O	O / O	O / O	O / O	O / O	O / O	O / O	O / O
Ln(F)	O / O	- / -	O / O	O / O	- / -	O / O	O / O	O / O	- / -	O / O	O / O	O / O	O / O	O / O
Ln(Tn/Rn)	O / - ^b	O / -	O / O	O / -	O / -	- / -	O / O	O / O	O / -	O / O	O / O	O / O	O / O	O / O

^aO : passed; ^b- : failed

between Tn and its progeny was calculated. The results of the calculation are presented in Fig. 8 (as an example) and in Table 3. It was found that the coefficient of determination (R^2) between all surveys is very weak and the R^2 parameter is low, being below 0.05.

In addition, the linear regression model was adopted for other measured parameters and the results are summarized in Table 3. As expected, the relationship between Rn and Tn is weak, with the coefficient of determination < 0.2 (with S3 and S5 being exceptions). The regression analysis also shows a poor correlation between Rn and TnP ($R^2 < 0.03$). These results suggest that the concentrations appear to be independent of each other.

Another important parameter for dose calculation is equilibrium factor (F_{Tn}). Results of the F_{Tn} calculation, defined as the ratio of TnP/Tn, are listed in Table 1. The range of mean values of this parameter for all data vary from < 0.01 to 0.04, with the median of < 0.01 to 0.02 and a range from < 0.01 to 0.57. It should be noted that UNSCEAR 2000

assumed average equilibrium factors (F_{Tn}) for Tn obtained from the $^{212}\text{Pb}/^{220}\text{Rn}$ ratio to be 0.02 indoors and 0.003 outdoors. As mentioned earlier the appropriate tests for normal and non-normal distributions were performed. Results of these calculations are shown in Table 4. If the distribution of F_{Tn} could be assumed to be log-normal (Table 2) the t-test was performed, otherwise the Wilcoxon test was performed; if the P -value was < 0.05 , the null hypothesis ($F_{Tn} = 0.02$) should be rejected. Only one set (S1) of original data and one set of modified data (S2m) show a positive result, $P > 0.05$.

Generally, the influence of Tn on Rn measurement is negligible due to its small value relative to that of Rn and to its short half-life time. But, in some cases the Tn concentration is much higher than that of Rn therefore more accurate evaluation of Rn is necessary. Earlier investigations of passive type detectors have shown the influence of Tn on Rn evaluation. For instance, Tokonami *et al.* [22] and Sugino *et al.* [10] showed that if the ratio of Tn/Rn

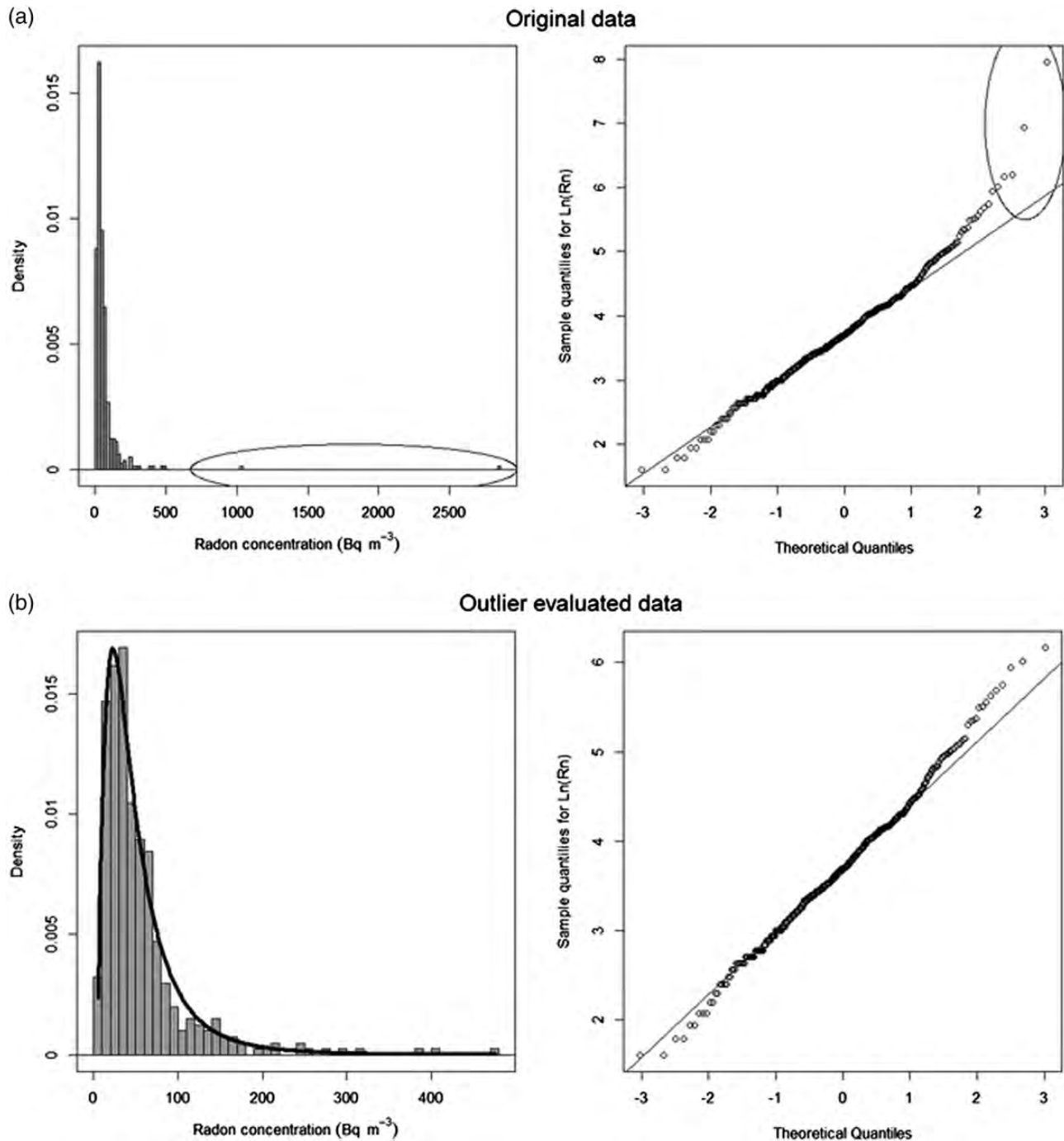


Fig 5. Histograms and Q-Q plot of radon concentration for S5 survey: (a) original data with indication of possible outliers by ovals and (b) outlier evaluated data (histogram with log-normal distribution).

exceeded 1.0, Rn concentration might be overestimated by about 4% by using a single Rn monitor, however a ratio of about 100 could modify results by a factor of 10. On the other hand, a ratio below 0.8 could not modify the Rn results. Moreover, some kinds of detectors tested by Tokonami *et al.* and Sugino *et al.* might provide a higher value of Rn than its actual concentration if the influence of Tn is not considered, especially close to the Tn source (wall,

ceiling, etc.). As mentioned earlier, for all six surveys studied discriminating Rn and Tn detectors were used. The calculated average Tn/Rn ratios ranged from 0.48–6.46, and the median from 0.37–3.79, with the absolute ranges from 0.03–78.25. In surveys S1, S2 and S5 the average concentrations of Tn were higher than Rn. Analysis of the data shows cumulative relative frequency distribution of ratios <0.8 from 1 to 83% (original data: S1 – 12%, S2 – 1%, S3 – 83%, S4

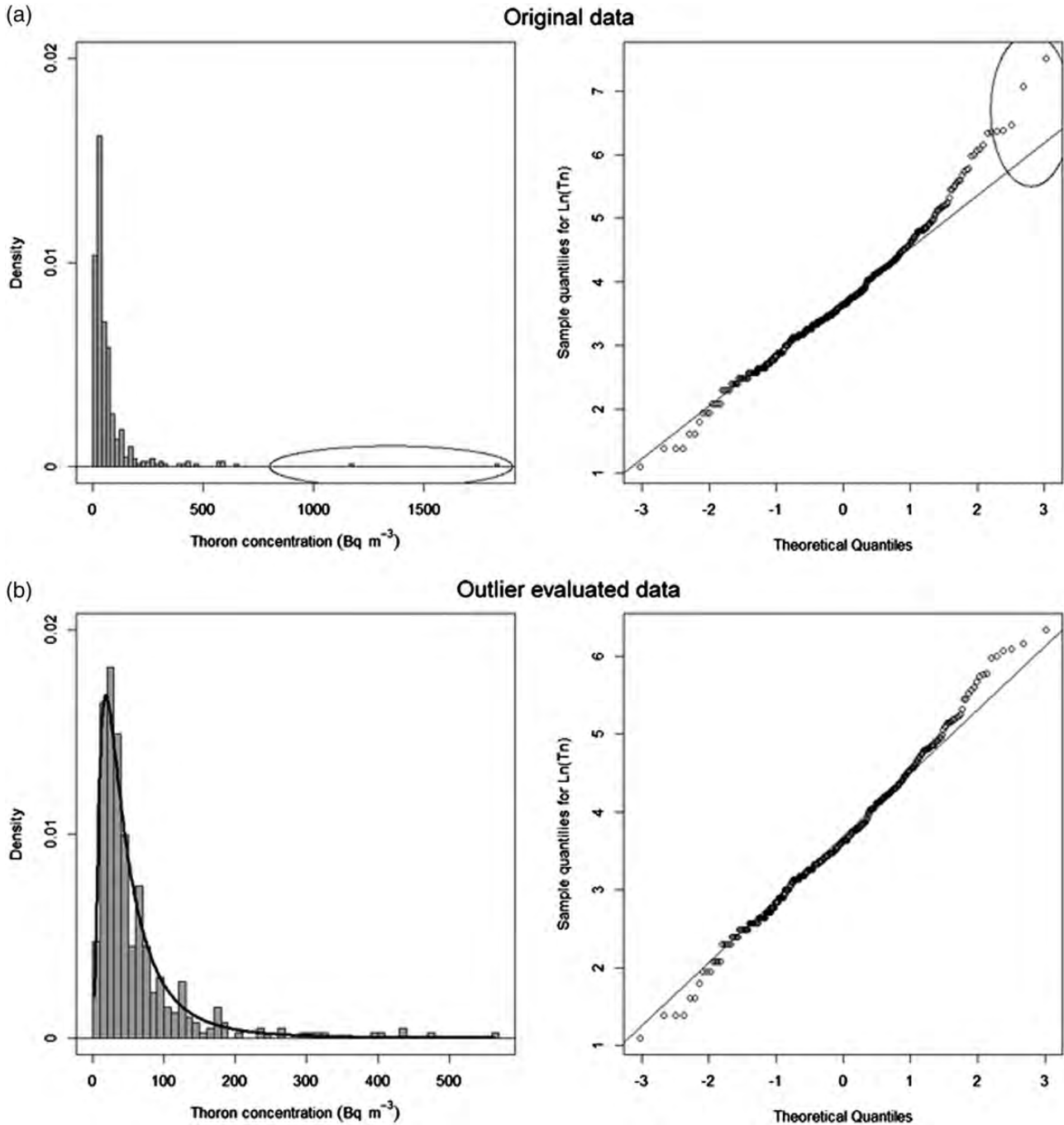


Fig 6. Histograms and Q-Q plot of thoron concentration for S5 survey: (a) original data with indication of possible outliers by ovals and (b) outlier evaluated data (histogram with log-normal distribution).

– 51%, S5 – 41%, S6 – 52%, and modified data: S2m – 1%, S3m – 82%, S4 – 48%, S5 – 41%, S6 – 52%) with 49% for the original data and 50% for all complied outlier evaluated data (Fig. 9b). The smallest values are obtained in the S1 and S2 surveys, dedicated to Tn investigation.

The above results, especially for the Tn equilibrium factor, suggest that in most cases TnP concentrations cannot be estimated from the observed concentration of Tn by assuming the Tn equilibrium factor provided by UNSCEAR for individual surveys. The effective dose can

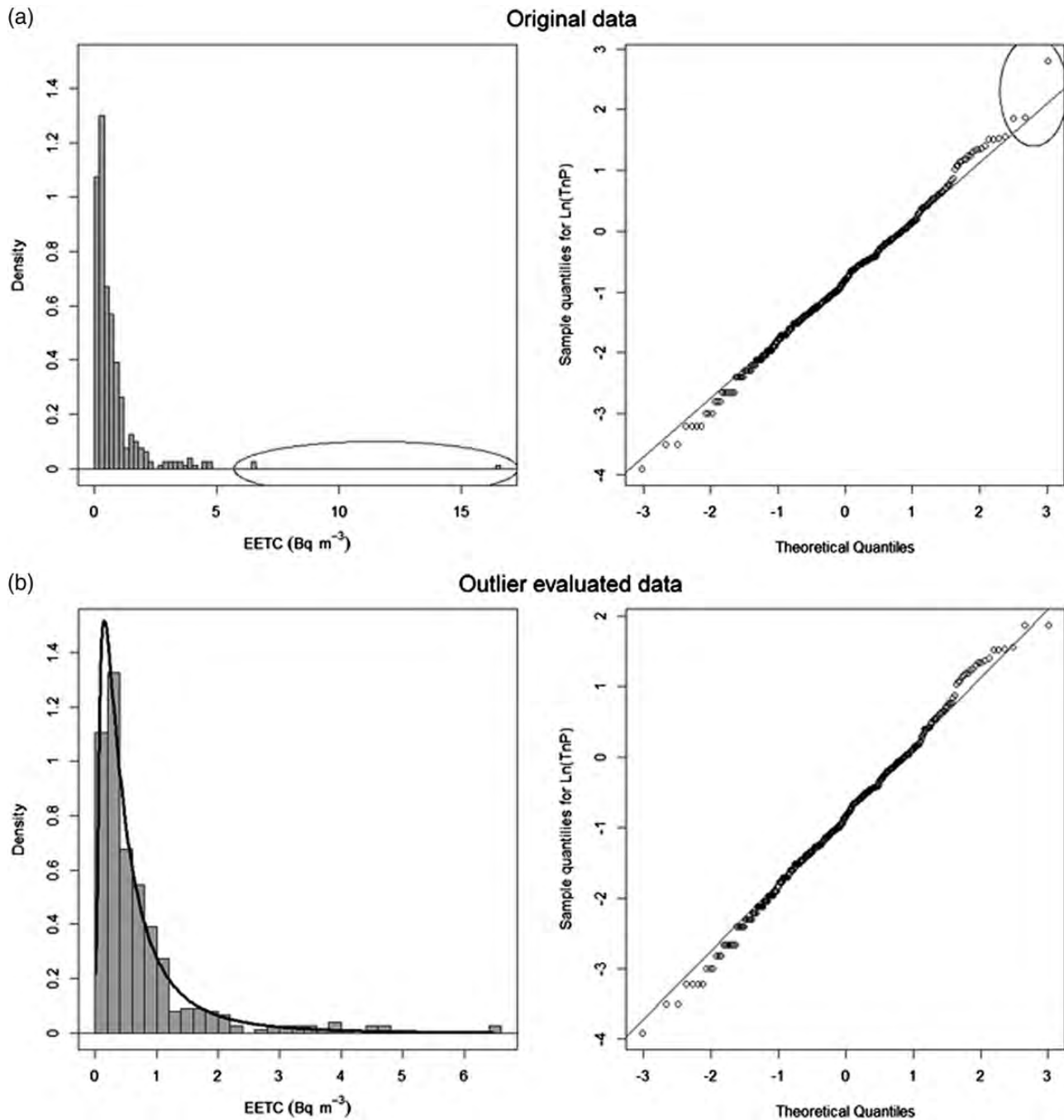


Fig 7. Histograms and Q-Q Plots of thoron progeny concentration for S6 survey: (a) original data with indication of possible outliers by ovals and (b) outlier evaluated data (histogram with log-normal distribution).

be estimated using the following equation:

$$H_{Tn} = EEC_{Tn} * t * DCF_{Tn} * F_{Tn} * t * DCF_{Tn}$$

where H_{Tn} is the annual effective dose for Tn decay products (mSv y^{-1}), EEC_{Tn} is the equilibrium equivalent Tn concentration (Bq m^{-3}), t is the indoor exposure time

(usually = 7000 h), DCF_{Tn} is the dose conversion factor for Tn ($= 40 \text{ nSv h}^{-1} \text{ Bq}^{-1} \text{ m}^3$), and C_{Tn} and F_{Tn} are as defined earlier. The above equation is very sensitive to F_{Tn} factor, e.g. for $C_{Tn} = 100 \text{ Bq m}^{-3}$ and $F_{Tn} = 0.008$ (minimum value from Table 1) the effective dose is $H_{Tn} = 0.24 \text{ mSv y}^{-1}$, but for $F_{Tn} = 0.038$ (maximum value) the calculated effective dose is about five times higher ($H_{Tn} = 1.06 \text{ mSv y}^{-1}$).

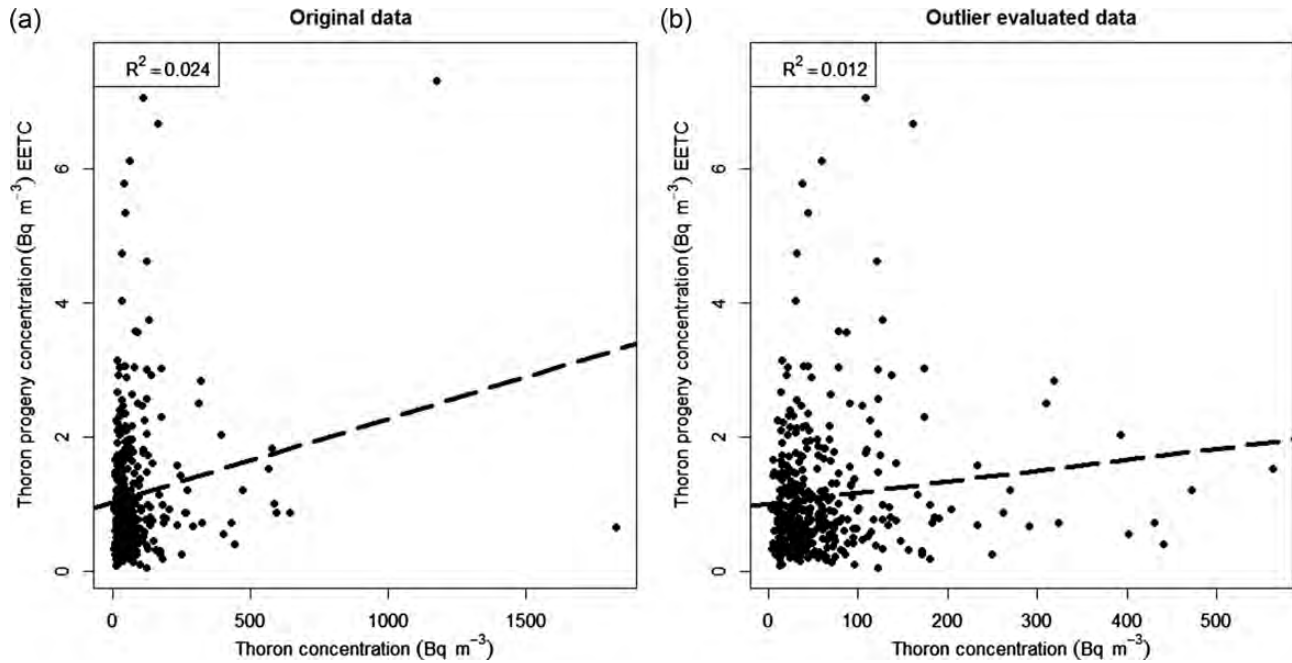


Fig 8. Correlation relationship between thoron and thoron progeny concentrations for S5 survey: (a) original data, (b) outlier evaluated data.

Table 3. Coefficients of determination R^2 for correlation between Rn, Tn and TnP results

Survey Parameter	Original data						Outlier evaluated data					
	S1	S2	S3	S4	S5	S6	S2m	S3m	S4m	S5m	S6m	
Rn – Tn	<0.01	0.01	0.43	0.03	0.48	0.12	0.01	0.44	0.01	0.19	0.16	
Rn – TnP	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	
Tn – TnP	0.04	0.01	<0.01	0.03	0.02	0.02	0.05	<0.01	<0.01	0.01	0.04	

Table 4. Results of Wilcoxon-test and t-test for $F_{Tn} = 0.02$ – recommended value by UNSCEAR 2000 [23]

Survey Parameter	Original data								Outlier evaluated data						
	S1	S2	S3	S4	S5	S6	All	S1m	S2m	S3m	S4m	S5m	S6m	All m	
Wilcoxon		- ^b													
t-test	O ^a		-	-		-	-	O	O	-				-	

^aO : passed; ^b -: failed

Therefore, if discriminative measurements are made without incorporating EEC_{Tn} data, the final effective dose might be over- or under- estimated.

Moreover, for the all merged data the F_{Tn} mean value is 0.032 with the range from 0.001–0.573 (with standard deviation of 0.047 and median value of 0.018). The low

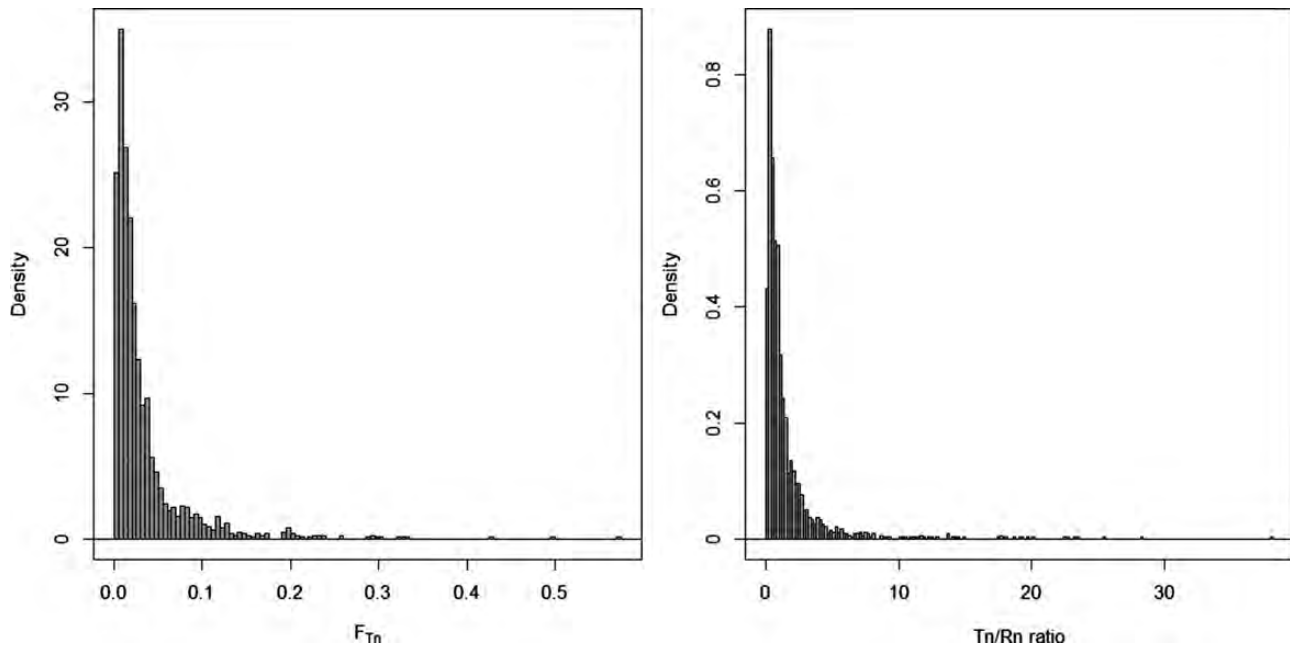


Fig 9. Histograms for F_{Tn} and Tn/Rn ratio for outlier evaluated data compiled from all six surveys.

P -value (<0.05) of the F_{Tn} t-test for merged data (the histogram of all six compiled surveys is presented in Fig. 9a) suggests that the UNSCEAR value should be revised if it is to be used for general applications and as a point of reference. On the other hand, the high variation of the equilibrium factor (by a factor of 10^3) as well as the high value of the standard deviation (more than 100% amount of mean value) may result in highly uncertain risk estimates of the effective dose whenever the F_{Tn} value is assumed to be that given by UNSCEAR.

CONCLUSION

A total of 1748 cases were analyzed from six surveys in different parts of the world. In no case was any linear relationship between Tn and its progeny concentrations found. Other analyzed parameters (Rn–Tn and Rn–TnP) also showed weak correlations but some exceptions (stronger correlations) were found.

From the viewpoint of dose assessment TnP measurement is important. However, it is difficult to estimate its concentration from Tn measurement and the typical Tn equilibrium factor as recommended by UNSCEAR. This is because the distribution of Tn concentration within a room varies quite strongly spatially and depends on the distance from its source. Moreover, high values (both mean and range) of the Tn/Rn ratio suggested that the results of Rn measurements without Rn–Tn discrimination might be overestimated if the detector is sensitive to Tn and the measurement is made by devices with no Rn–Tn discrimination capability. It was concluded from the various surveys

that, for good estimation of the Rn and Tn dose, measurements of Rn, Tn and their progeny concentrations should be carried out simultaneously.

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