EVOLUTION OF RADON DOSE EVALUATION

by

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The historical change of radon dose evaluation is reviewed based on the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) reports. Since 1955, radon has been recognized as one of the important sources of exposure of the general public. However, it was not really understood that radon is the largest dose contributor until 1977 when a new concept of effective dose equivalent was introduced by International Commission on Radiological Protection. In 1982, the dose concept was also adapted by UNSCEAR and evaluated *per caput* dose from natural radiation. Many researches have been carried out since then. However, lots of questions have remained open in radon problems, such as the radiation weighting factor of 20 for alpha rays and the large discrepancy of risk estimation among dosimetric and epidemiological approaches.

Key words: radon, effective dose, equivalent dose, indoor radon survey, electro-chemical etching, thoron

INTRODUCTION

Radon had been suspected to be the cause of lung cancer detected in uranium miners for a long time. However it was not confirmed until the middle of 20th century. It is now clear that the main cause of lung cancer among uranium miners resulted from their exposure to radon progeny in mines. Additional effort was made to investigate positive relationship between the occurrence of lung cancer and radon exposure in houses. In some cases studies showed positive correlation and in some they did not. On the other hand, radon gas was used as a healing tool in medical field in treating arthritis or other diseases in radon spas for a long time. Beneficial effects on the symptoms of radon exposure treatments were reported. International Commission on Radiological Protection (ICRP) made the Como statement concerning radon gas usage in radon spas for medical treatment in 1987 [1]. The following was stated: such exposures should take place if, and only if, national authorities and the individual practitioners are satisfied that the procedure has a positive net benefit for the patient and that the exposure is reduced to levels estimated to be efficacious. Therefore, radon is still a big issue and requires further studies to clarify the effects due to radon exposure especially in the relatively low range of exposure. In the present paper radon dose evaluation is reviewed based on reports of United Nation Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in connection with ICRP Recommendations.

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UNSCEAR 1958-1962

From the very foundation of UNSCEAR in 1955 attention was focused on the assessment of dose due to natural radiation including radon and thoron. UNSCEAR published summary reports in 1958, 1962, 1966, 1972, 1977, 1982, 1988, 1993, and 2000, every 5 or 6 years reviewing the current scientific knowledge and information [2– 10]. Table 1 shows the list of summary reports of UNSCEAR together with some relevant ICRP publications.

In 1958 Report doses were estimated for critical organs due to natural radiation including radon and thoron [2]. Gonad, bone living cells, red bone marrow was considered to be the critical organs at that time. Doses were estimated in the unit of mrem

Table 1. List of UNSCEAR reports with relevant ICRP publications

UNSCEAR	1958		1962	1966	1972	1977	1982	1988		1993	2000
	[mrem]		[mrem]	[mrad]	[mrad]	[mrad]	[mSv]	[mSv]		[mSv]	[mSv]
				RBE uncertain							
Gonad	ext. 2 int. 2		3	0.3	0.073	0.2					
Bone lining cells	osteocyte ext. 2 int. 0		Havarsian canal 3	Havarsian canal 0.3	0.13	0.4					
Red bone marrow	ext. 2 int. 2		3	0.3	0.13	0.4					
Lung	critical organ		100-900	a few hundreds		34					
Tracheo-bronchial					55-195	160					
Rn							0.8	1.1		1.2	1.15
Tn							0.17	0.16		0.07	0.1
Total due to natural radiation	gonad 100		gonad 125 (102 mrad)	gonad 100	gonad 93	gonad 78	2.0	2.4		2.4	2.4
		1959		1966		1977			1990		
ICRP		2		9		26			60		
Tissue weighting factor for lung						w_T: 0.12			w_T: 0.12		
Radiation weighting factor	RBE: 10	RBE: 10		QF: 10		Q: 20			w_R: 20		

using RBE of 10 for alpha particles. All doses in the critical organs due to radon and thoron exposure were small comparing to other sources of natural radiation. It is because the exposure to radon and thoron is mainly the result of inhalation. The most exposed organ especially to radon is lung due to shorter half-life of radon progeny.

Table 2 was quoted from Table I in UNSCEAR 1958 Report [2]. The total dose due to natural radiation was estimated to be 100 mrem as gonad dose.

Table 2. Annual doses from Natural Radiation Sources (Table I in UNSCEAR 1958)

Source	Annual dose		
	Gonad dose [mrem]	Osteocyte dose [mrem]	Mean marrow dose [mrem]
External			
Cosmic rays	28	28	27
Terrestrial radiation	47	47	47
Atmospheric radiation	2	2	2
Internal			
K-40	19	11	11
C-14	1.6	1.6	1.6
Rn-Tn	2	–	2
Ra	–	38	0.5
Approximate totals*	100	130	95

* The totals in the table are "normal" natural radiation intensities; in certain areas the values range up to ten times higher than those given

The largest dose came from terrestrial radiation followed by cosmic rays. Potassium 40 gave a relatively large dose as internal exposure. As a contrast, the doses due to radon and thoron were small and estimated to be 2 mrem for gonad and bone marrow that is only two percent of the total dose.

However, even in the earliest UNSCEAR report, the lung dose was estimated using the data of Dr. Hultqvist as shown in tab. 3, that is a citation from Table 24 in UNSCEAR 1958 [2]. The results were summarized for each type of houses based on data from Sweden. Large doses in lungs were demonstrated although RBE of 10 for alpha rays was used in dose estimation. Relatively high dose in the lung due to radon and its progeny in the normal natural environment was recognized early in 1958. However, not only radiation protection specialists but also the general public did not pay much attention to radon exposure because it was localized only in the lung and gave small a dose in gonad or bone marrow. Dose estimation regarding radon and thoron in UNSCEAR1962 Report was almost the same as that in 1958 as shown in tab. 1. [3]

UNSCEAR 1966-1977

The doses in UNSCEAR1966 report were estimated in the unit of rad instead of rem because they considered that RBE was very uncertain in dose esti-

Table 3. Doses to lungs from radon and thoron in the air (based on measurements carried out in Sweden) (Table XXIV in UNSCEAR 1958)

Outer wall	Concentration of Rn in c/l 10^{12}		Concentration of Tn in c/l 10^{12}		Dose in mrem per year			
					Rn		Tn	
	assuming equilibrium	with ventilation 10^{-8} s	assuming equilibrium	with ventilation 10^{-8} s	in equilibrium	with ventilation	in equilibrium	with ventilation
Wood	0.527	0.537	0.0278	0.136	263	73	185	52
Brick	0.909	0.913	0.0910	0.450	453	128	605	173
Light weight concrete (contain. alum shale)	1.86	1.86	0.0959	0.461	930	262	640	178

mation [4]. Therefore, the results shown in tab. 1 in the column of year 1966 were different from the figures for the year of 1962. If RBE of 10 is applied to the values in year 1966, the results are the same as the ones in the year of 1962. For the sake of comparison, the total dose estimation in the unit of rad was also shown in the column of year 1962.

In the same year of 1966, ICRP Pub. 9 introduced Quality Factor (QF) instead of RBE as one of the modifying parameters in dose estimation taking into account the difference of health effects by radiation types [11]. The UNSCEAR Reports in 1972 and 1977 dealt with radon as before although the figures were slightly different based on the data available at the time [5, 6]. In addition, those reports mentioned the regional dose estimation in trachea and bronchia as critical tissue dose due to radon and its progeny. The estimation showed a relatively high absorbed dose.

As shown in tab. 4 which is the citation from Table 31 in UNSCEAR 1977 Report demonstrated more detailed dose estimation from various natural sources to critical organs including lungs [6]. The lung dose was estimated to be 30 mrad for radon, and 4 mrad for thoron which were relatively large compared with other sources.

In the same year of 1977 ICRP Pub. 26 was published [12]. It introduced effective dose equiva-

Table 4. Estimated annual tissue absorbed dose from natural sources in normal areas (Table 31 in UNSCEAR 1977)

Source of irradiation	Annual tissue absorbed dose [mrad]						
	Gonads		Lung	Bone lining cells		Red bone marrow	
External irradiation							
Cosmic rays:							
Ionizing component	28	(28)*	28	28	(28)	28	(28)
Neutron component	0.35	(0.35)	0.35	0.35	(0.35)	0.35	(0.35)
Terrestrial radiation: ( )	32	(44)	32	32	(44)	32	(44)
Internal irradiation							
Cosmogenic radionuclides:							
^{3}H ( )	0.001	(0.001)	0.001	0.001	(0.001)	0.001	(0.001)
^{7}Be ( )	–	–	0.002	–	–	–	–
^{14}C ( )	0.5	(0.7)	0.6	2.0	(0.8)	2.2	(0.7)
^{22}Na ( )	0.02	–	0.02	0.02	–	0.02	–
Primordial radionuclides:							
^{40}K (	15	(19)	17	15	(15)	27	(15)
^{87}Rb ( )	0.8	(0.3)	0.4	0.9	(0.6)	0.4	(0.6)
^{238}U-^{234}U ( )	0.04	(0.03)	0.04	0.3	(0.3)	0.07	(0.06)
^{230}Th ( )	0.004	–	0.04	0.8	–	0.05	–
^{226}Ra-^{214}Po ( )	0.03	(0.02)	0.03	0.7	(0.6)	0.1	(0.1)
^{210}Pb-^{210}Po (	0.6	(0.6)	0.3	3.4	(1.6)	0.9	(0.3)
^{222}Rn-^{214}Po ( )inhalation	0.2	(0.07)	30	0.3	(0.08)	0.3	(0.08)
^{232}Th ( )	0.004	–	0.04	0.7	–	0.04	–
^{228}Ra-^{208}Tl ( )	0.06	(0.03)	0.06	1.1	(0.3)	0.2	(0.06)
^{220}Rn-^{208}Tl ( )inhalation	0.008	(0.003)	4	0.1	(0.05)	0.1	(0.05)
Total (rounded)	78	(93)	110	86	(92)	92	(89)
Fraction of absorbed doses delivered by alpha particles or neutrons [%]	1.2	(1.3)	3.1	8.5	(4.1)	2.1	(1.2)

* Results of previous assessment in parentheses

lent as a new dosimetric quantity, *i. e.*, the sum of doses in all tissues and organs. Dose unit was also changed from rem to Sv. The tissue weighting factor for lungs was chosen to be 0.12 taking into account relative importance of lung cancer risk to others. In addition, quality factor was doubled for alpha rays. It led to a sudden increase of risk due to alpha rays.

UNSCEAR 1982-1988

Based on the new dosimetric quantity of effective dose equivalent and the new quality factor, the dose contribution of radon and thoron became more apparent as you can see in tab. 5 (cited from Table 17 in UNSCEAR 1982 Report), *i. e*., 800 Sv from radon and 170 Sv from thoron [7]. Total dose from natural radiation was estimated to be 2000 Sv = 2 mSv that is about twice as large as the former value. Half of this dose came from radon and thoron. Radon was not disregarded any more as the source that causes exposure only of the lungs. It became a rather big concern of the society. In addition, the general public could not easily understand the increase of total dose due to natural radiation. The change unfortunately caused mistrust of the general public in the specialists of radiation protection society. The radiation protection specialists made a lot of effort to explain the real meaning of dose increase. This was not due to the reevaluation of radiation risk or mistake of previous evaluations, but rather to a different approach in the presentation of dose estimation.

Based on the way of calculation using effective dose equivalent radon drew more attention than before. However, not many data on radon concentrations were available at that time as shown in tab. 6 (cited from Table 40 in UNSCEAR 1982 Report) [7]. The numbers of houses measured in these surveys were 3436, 35, 250, 129, 600, and 87 for Canada, Finland, Federal Republic of Germany, Norway, Sweden, and United Kingdom, respectively. Not many countries have finished nation-wide surveys yet.

In the early eighties, the chairperson of UNSCEAR was the director general of the National Institute of Radiological Sciences (NIRS) in Japan and he requested every member state to carry out a nation-wide indoor radon survey for the population dose estimation. The NIRS Institute received his request readily and initiated radon survey. The doses due to radon and thoron were reevaluated in addition to other natural sources in UNSCEAR Report 1988 [8]. The doses due to radon and total dose were a little higher than before as shown in the column of year 1988 in tab. 1

Table 5. Estimated *per caput* annual effective dose equivalents from natural sources in areas of normal background (Table 17 in UNSCEAR 1982)

Source of irradiation	Annual effective dose equivalent [Sv]		
	External irradiation	Internal irradiation	Total
Cosmic rays			
– ionizing component	280		280
– neutron component	21		21
Cosmogenic radionuclides		15	15
Primordial radionuclides			
^{40}K	120	180	300
^{87}Rb		6	6
^{238}U series			
^{238}U ^{234}U		10	
^{230}Th		7	
^{226}Ra	90	7	1044
^{222}Rn ^{214}Po		800	
^{210}Pb ^{210}Po		130	
^{232}Th series			
^{232}Th		3	
^{228}Ra ^{224}Ra	140	13	326
^{220}Rn ^{208}Tl		170	
Total (rounded)	650	1340	2000

UNSCEAR 1993-2000

In 1990 ICRP revised its recommendation as Pub. 60 from its old recommendation of Pub. 27 [13, 14]. New dosimetric quantities were introduced. "Effective dose equivalent" was changed to "effective dose" and "dose equivalent" to "equivalent dose." The name of quality factor defined to different type of radiation was changed to "radiation weighting factor". The UNSCEAR Report in 1993 calculated the dose using the new dosimetric quantity of effective dose [9]. The values in the report were not very different from the previous report although there was a small decrease of thoron contribution based on recently available data.

The latest UNSCEAR Report in 2000 showed almost the same results as in 1993 Report [10, 9]. The Committee had a heated discussion for a few years on "conversion convention" that was proposed by ICRP Pub. 65 in 1993 and finally decided not to use the factor, but to continue to use its own way of radon dose estimation [15]. Table 7 shows doses from each component of natural sources including radon and thoron as well as their typical ranges. Radon provides dose of 1.15 mSv/year and thoron of 0.10 mSv/year. The sum of radon and thoron dose contribution covers more than 50% of the total dose of 2.4 mSv/year. And their typical range goes up to 10 mSv/year.

Table 6. Equilibrium equivalent concentrations of radon and annual effective dose equivalents for dwellings of different types in various countries (Table 40 in UNSCEAR 1982)

Country or area	Structure	Equilibrium equivalent concentration [Bqm^{-3}]	Annual effective dose equivalent [mSv]	Ref.
Austria	Average for Salzburg	12	0.7	[S22]
Canada	Typical Canadian homes	17	1.0	[M6]
Denmark	Basement room, thick structured elements	4.8	0.3	[N2]
Finland	Flats other than groundfloor	17	1.0	[N2]
Germany, Fed. Rep.	Average for 32 houses	8.1	0.5	[W14]
Hungary	Isolated rooms	20	1.2	[N2]
	As specified in Table 28, Annex B [U6]	120	7.3	[U6]
Norway	Flats other than groundfloor	11	0.7	[N2]
	Average value	26	1.6	[S24]
Poland	Average value	6-17	0.4-1.0	[G13, B16, B17, U6]
Sweden	Average value	60	3.7	[R15]
United Kingdom	Single-family houses	15	0.9	[N2]
	Average value	13	0.8	[C6]
United Sates	New Jersey and New York and as specified in Table 28, Annex B [U6]	15	0.9	[U6]
USSR	Flats other than groundfloor	4.8	0.3	[N2]
	Single-family houses and groundfloor flats	16	1.0	[N2]
Several countries	Mainly masonry houses and apartments	18	1.1	[U6]

IN JAPAN

In accordance with the UNSCEAR's request a radon survey was conducted by the NIRS group in Japan during 1985 and 1991 [16]. A robust, inexpensive and reliable passive detector was searched for to be used in the nation-wide survetry. Karlsruhe type passive radon detector was then chosen for the survey. The passive detector has a small chamber covered by a glass fiber filter that prevents penetration of radon progeny into the cup. At the bottom of the cup a film of polycarbonate was placed. After exposure films were treated by chemical and electrochemical etching using KOH and ethanol as etching solution with the power supply of 800 V, and 2 kHz of frequency.

Figure 1 shows an electrochemical etching mechanism to demonstrate the etch pit formation. When an alpha particle enters a polycarbonate film large portion of its energy is delivered at the end of

Table 7. Average worldwide exposure to natural radiation sources (Table 31 in UNSCEAR 2000)

Source of exposure	Annual effective dose [mSv]	
	Average	Typical range
Cosmic radiation		
Directly ionizing and photon component	0.28 (0.30)[a]	
Neutron component	0.10 (0.08)	
Cosmogenic radionuclides	0.01 (0.01)	
Total cosmic and cosmogenic	0.39	0.3-1.0[b]
External terrestrial radiation		
Outdoors	0.07 (0.07)	
Indoors	0.41 (0.39)	
Total external terrestrial radiation	0.48	0.3-0.6[c]
Inhalation exposure		
Uranium and thorium series	0.006 (0.01)	
Radon (^{222}Rn)	1.15 (1.2)	
Thoron (^{220}Rn)	0.10 (0.07)	
Total inhalation exposure	1.26	0.2-10[d]
Ingestion exposure		
^{40}K	0.17 (0.17)	
Uranium and thorium series	0.12 (0.06)	
Total ingestion exposure	0.29	0.2-0.8[a]
Total	2.4	1-10

[a] Result of previous assessment [U3] in parentheses
[b] Range from sea level to high ground elevation
[c] Depending on radionuclide composition of soil and building materials
[d] Depending on indoor accumulation of radon gas
[e] Depending on radionuclide composition of foods and drinking water

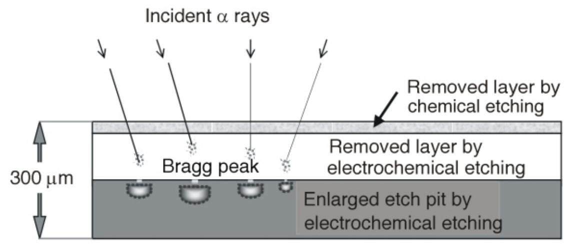

Figure 1. Electro-chemical etching

trajectory. The densely ionized site is called Bragg peak. Only the Bragg peaks turn to the etch pits after the electrochemical etching in polycarbonate films. Upper layer is removed by chemical etching. All the defects in the upper layer were eliminated by this process. The defects made by Bragg peak in the second layer were enlarged by electrochemical etching.

In this connection, merit and demerit of electrochemical etching is mentioned briefly with the comparison of chemical etching. Polycarbonate could not make etch pit by chemical etching. If etch pits are desired to be made by chemical etching, CR39, LR115 or other materials have to be used for detectors. Background etch pit density by electrochemical etching is lower than chemical etching since surface defects caused by physical or chemical attack on the surface were eliminated by chemical etching prior to electrochemical etching. The price of polycarbonate is low. Electrochemical etching provides energy information of incident alpha particles by selecting the duration of chemical and electrochemical etching. In addition, etch pit size produced by electrochemical etching is larger and could be counted by naked eyes. However, the drawbacks of electrochemical etching were smaller range of measurable radon concentration, higher price of etching devices and time consuming of etching procedure.

Our nation-wide survey by Karlsruhe type passive detectors is briefly mentioned here. At first an attempt was made to make a random sample of houses for measurements from telephone directories. Postcards were then sent to the chosen houses with return mail asking cooperation in our survey. Less than 20% replied to our request. Unfortunately, this random approach had to be given up since it turned out to be a waste of money for postage. An alternative way was to obtain name lists of teachers from the science teacher association in senior high schools although this method was not a random sampling. With this approach the consent for measurement cooperation was obtained from more than 7,000 houses throughout Japan. That number corresponds to 0.017% of the total house stock in Japan. The intention was to obtain annual average indoor radon concentrations for the estimation of the dose of the general public.

Two passive radon detectors were usually placed on a cupboard or a desk in the living room and bedroom of selected houses for two successive six months to cover a whole year.

Figure 2 is the result of our survey (5717 houses). The median of nationwide survey of Japan is 16.0 Bqm^{-3}, and its average is 20.8 Bqm^{-3}. Japanese houses have relatively lower radon concentrations in comparison with other countries. The survey demonstrated that the percentage of houses with high radon concentration that is above 150 Bqm^{-3} was only 0.4% of the house stock in Japan. In spite of the original description of the detector Karlsruhe type passive radon detector was found to have higher air exchange rate than expected and showed radon concentrations that were affected by thoron especially in traditional Japanese wooden houses with clay walls. Some of this type of houses in the western part of Japan show high thoron concentrations.

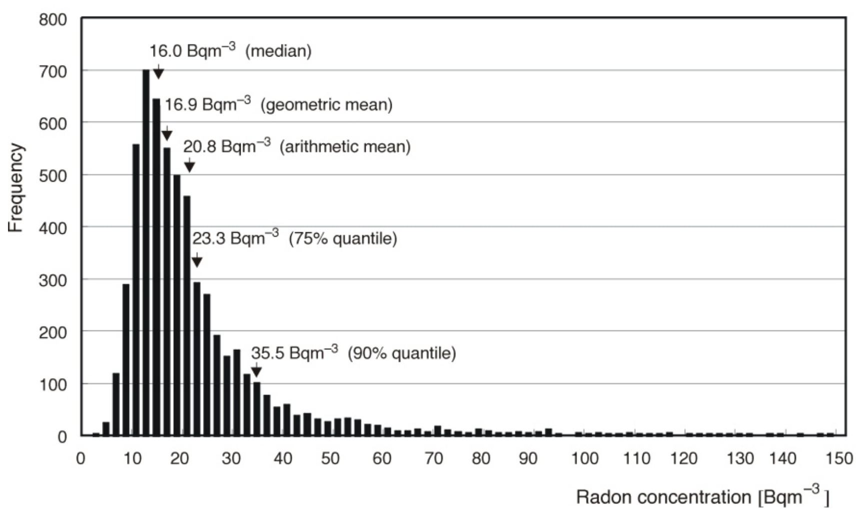

Figure 2. Result of nation-wide survey (1985-1991)

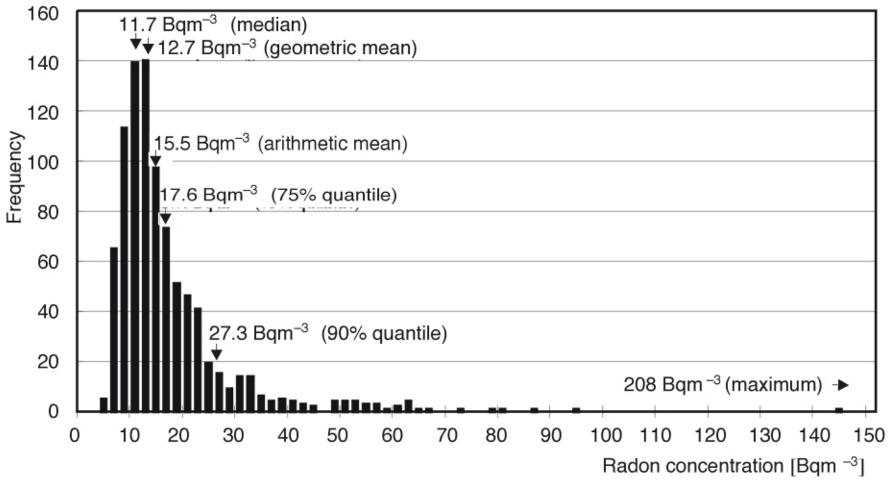

Figure 3. Result of second nation-wide survey (1992-1996)

In order to solve the interference of thoron in radon measurement a new passive detector (UFO type) was designed to discriminate radon from thoron [17, 18, 19]. This passive radon and thoron detector has two hemispheres; one for radon and the other for radon and thoron. The second nation-wide survey using the UFO type detector was conducted during 1992 and 1996 with a relatively small number of houses – 899 [20]. Figure 3 demonstrates the histogram of the results. The median of nation-wide survey of Japan is 11.7 Bqm^{-3}, and its average is 15.5 Bqm^{-3}. They were about 5 Bqm^{-3} lower than the first nationwide survey. The reason of the difference could be thoron contribution or the different approach to the survey at different time.

FURTHER DEVELOPMENT IN JAPAN

Both our nationwide indoor radon surveys showed that the radon concentration levels in Japan are much lower than the world average of 40 Bqm^{-3} [10]. Radon could not be an urgent social concern and no action has been prescribed yet by regulations. Therefore, attention was shifted to more precise radon dose estimation in Japan such as radon concentration measurements during working hours [21] or radon survey for working environments or environmental aerosol measurements. In addition, other types of survey to find out high radon areas were conducted at caves, underground shopping arcades or subway stations. The correlation between indoor radon concentration and dose rate in air due to terrestrial gamma radiation was also investigated based on nation-wide radon and gamma surveys [22]. It was established that the average radon concentration increase with the gamma ray dose rate in the air. Based on the finding a certain criterion level of air dose rate could be established and used for an effective survey to find out which houses might require a remedial action in conjunction with other screening tools. Time trend of indoor radon concentration was also one of the issues the society should consider for the plan of future healthy environment [23]. Throughout the long history of wooden houses in Japan its indoor radon concentration does not seem to have changed much judging by the year of construction which goes back to a few hundred years ago. However, concrete houses show a steady increase of indoor radon concentration. The reason of recent increase of indoor radon concentration might be due to airtight construction for the purpose of energy conservation.

Estimation of population dose or *per capita* dose due to natural radiation has been an important issue in UNSCEAR. Further radon concentration surveys in the outdoor and working environments have been conducted by Japan Chemical Analysis Center to complete the nation-wide radon survey. Cosmic ray dose was estimated by using a computer code developed by K. O'Brien and geographical data as another important component of natural radiation [24]. The cosmic ray dose at each municipality was published in the form of data tables and maps with the same type of map for indoor radon concentrations [25, 26].

TECHNIQUE TRANSFER

After the finalization of our indoor radon surveys in Japan, we tried to find out some country that would use our devices for electrochemical etching. China, Viet Nam, Bangladesh, and Yugoslavia were candidates for the donation. During 1998 to 2001 a cooperative study between VINČA Institute of Nuclear Sciences, Belgrade, and NIRS was carried out for the radon and thoron measurements in Gornja Stubla at Province of Kosovo and Metohia [27, 28,

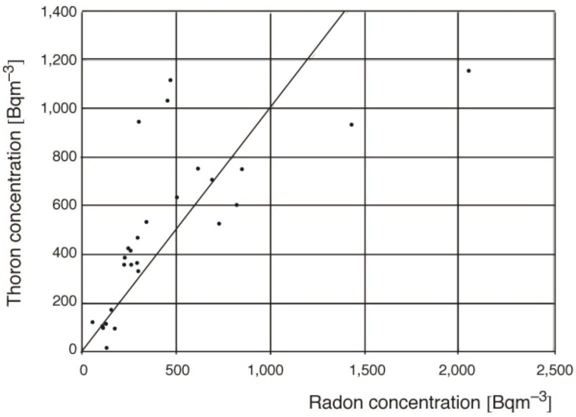

Figure 4. High radon and high thoron in Gornja Stubla

29]. Very high radon and thoron concentrations were found there as shown in fig. 4. This is an important and unique finding since the concentration was high for radon as well as thoron. Due to this unique situation as well as the high interest of researchers at VINČA Institute and NIRS for the measurements in Gornja Stubla, a research agreement was signed between National Institute of Radiological Sciences and VINČA Institute in November 2002.

FOR THE FUTURE

All devices related to electrochemical etching as well as UFO type passive radon thoron detectors were donated to VINČA Institute from Japan in November 2002. The devices are expected to be used intensively in this region since they have relatively high radon and thoron concentrations. Celebrating the establishment of the laboratory in VINČA Institute that is dedicated to the electrochemical etching, a workshop was organized to contribute to full understanding of the importance of radon and thoron problems as well as of electrochemical etching technique and to discuss future plan in this region.

Following subjects are considered to be the potential usages of the laboratory in this region:

Radon/thoron concentration estimation: nation-wide, special high background areas.

Other application: neutron flux measurements, neutron energy spectrum measurements, polymer lattice defect mechanism, and development of new methods for radiation measurements.

We believe good research works that are closely related to the concerns of people in local communities in this region will continue to be carried out based on a strong cooperation enhanced in the workshop [30, 31]. We wish successful future research work in this region.

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РАЗВОЈ ПРОЦЕЊИВАЊА ДОЗЕ РАДОНА

Начињен је преглед развоја процењивања дозе радона заснован на извештајима Научног комитета Уједињених Нација за ефекте атомског зрачења (UNSCEAR Reports). Од 1955. године, радон је сврстан међу значајне изворе излагања људског друштва. Међутим, није уочено да радон највише доприноси дози, све док 1977. године од стране Међународне комисије за радиолошку заштиту (ICRP) није уведен нови концепт ефективне еквивалентне дозе. У 1982. години, концепт дозе био је даље прилагођен и процењена је *per caput* доза зрачења из природе. Од тада су обављена бројна истраживања. Ипак, многа питања у вези радона остала су отворена, на пример, радијациони тежински фактор 20 за алфа зрачење и велика несагласност у процени ризика између дозиметријских и епидемиолошких приступа.