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RADON DOSE IN CELLARS DURING THE WAR IN CROATIA

J. Planinić*, N. Lokobauer, Z. Franić, A. Bauman

*Faculty of Education, Strossmayer University, Osijek,
Institute for Medical Research and Occupational Health,
University of Zagreb, Zagreb, Croatia

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During the war in 1991 and 1992, because of artillery bombardment, the citizens of Croatia have been forced to live underground in shelters and cellars and therefore they have been exposed to an additional radon radiation. Rn concentration in shelters (cellars) and dwellings of Osijek and Zagreb were measured by means of a silicon detector (Radhome) and also, at several locations, by an LR-115 nuclear track detector. Estimated monthly radon exposures in dwellings and cellars of Osijek or Zagreb were $(2.88\pm1.58)\times10^4$ Bq h m^{-3} and $(6.62\pm3.17)\times10^4$ Bq h m^{-3}, respectively, or $(1.94\pm0.72)\times10^4$ Bq h m^{-3} and $(7.46\pm7.78)\times10^4$ Bq h m^{-3}. Inhabitants of Osijek and Zagreb have received, on the average, the effective dose equivalent of 4.1 and 2.6 mSv y^{-1}, respectively.

INTRODUCTION

Indoor and outdoor radon (Rn) activity concentrations were measured by means of an LR-115 nuclear track detector in Osijek earlier and seasonal Rn variations

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in air were investigated for a few years[1]. The war against Croatia (unexpected and senseless) in 1991 and 1992 has drastically changed the way of life of the citizens and beyond large damages due to the bombardments), the people have had to live underground in shelters and cellars. So the citizens were exposed to an additional radon radiation and larger harmful doses. Inhabitants of east Croatia (e.g. towns as Vukovar and Osijek, as well as nearby villages) have got the greatest suffering, while towns on the west (e.g. Zagreb) have had fewer, air raid alarms. Therefore, Osijek and Zagreb were chosen as representative towns for radon dose equivalent assessments under war conditions.

METHODS, RESULTS AND DISCUSSION

Locations for indoor radon measurements in Osijek and Zagreb were selected in different parts of the towns, but houses with larger shelters (more people) were chosen, as well as houses of the acquaintances, which means the choice of the positions was not quite at random. It is to be noted that a statistical choice under war conditions was very difficult to realize because many dwellings were destroyed and abandoned.

Radon concentrations in shelters or cellars and dwellings of Osijek and Zagreb were measured by means of a Radhome (R) silicon detector (CMRP, France) and also, at several locations, by an LR-115 nuclear track detector (Kodak-Pathé, France). The R detector measured α-activities of radon-222 (^{222}Rn) and thoron (^{220}Rn) in air over 36 h or less in case of recording hundred impulses (internal device logic). A detector impulse per hour corresponded to a radon concentration of 50 Bq m^{-3} in air. A relative statistical error of the R detector, expressed as the variation coefficient or ratio of the standard deviation to the arithmetic mean was near 20%.

Radon concentrations in shelters and cellars of Osijek measured by the R detector (Table 1, Fig. 1) had an arithmetic mean of 92 Bq m^{-3}, with a standard deviation of (44), and the geometric average value of 76 Bq m^{-3} (45), but the respective average values in dwellings were 40 (22) and 36 (21) Bq m^{-3}.

Considering the mentioned arithmetic means and standard deviations of radon concentrations, estimated monthly exposures in dwellings and cellars of Osijek were $(2.88\pm1.58)\times10^{4}$ and $(6.62\pm3.17)\times10^{4}$ Bq h m^{-3}, respectively.

The arithmetic mean of the ratios of radon concentrations in cellars (c_c) to the ones in dwellings (c_d) was 2.31, with a standard deviation of 1.06.

At locations 6, 8, and 10 in Osijek, Rn concentrations were also measured by means of the LR-115 detector and the respective values of 37, 19, and 92 in cellars, then 15, 12, and 58 Bq m^{-3} in dwellings were obtained. Open and filtered α-track detectors were exposed in air for two months, afterwards etched in 10% aqueous NaOH solution at 60 ^{o}C (333 K) for 120 min and counted visually by a microscope, which gave the respective track densities D (open) and D_o (filtered) in (tr $cm^{-2}d^{-1}$). Radon concentration in air (c_o) was determined by means of the relationship:

$$c_o = \frac{D_o}{k} \quad , \qquad (1)$$

where the detector sensitivity was k = 0.030 tr $cm^{-2}d^{-1}$ $Bq^{-1}m^{3}$ (=0.346 cm)^{2}.

TABLE 1

Radon concentrations (Bq m^{-3}) in dwellings (c_d, with the floor ordinal numbers in houses) and cellars (c_c) at locations in Osijek, the ratio of concentrations c_c/c_d, and respective main building materials: concrete (c) and brick (b)

Location	c_d	(floor)	c_c	c_c/c_d	Material
1	32	(IV)	91	2.84	b
2	79	(II)	150	1.90	b
3			40		c
4	29	(X)			b, c
5	45	(II)	53	1.18	b
6	29	(V)	78	2.70	b, c
7	24	(V)	35	1.46	b, c
8	19	(I)	22	1.16	b
9	20	(IV)			b
10	100	(I)	184	1.84	b
11	40	(II)	104	2.60	b
12	44	(I)	98	2.23	b, c
13	35	(I)	83	2.37	b, c
14	21	(I)	108	5.14	b
15	49	(I)			b
16	33	(II)			b
17	43	(I)			b, c
18			102		b
19	31	(II)			b, c

Using the track densities D and D_o, the equilibrium factor (F) between radon and its daughters was calculated by the following equation[2]:

$$F = a \exp(bD_o/D) \qquad (2)$$

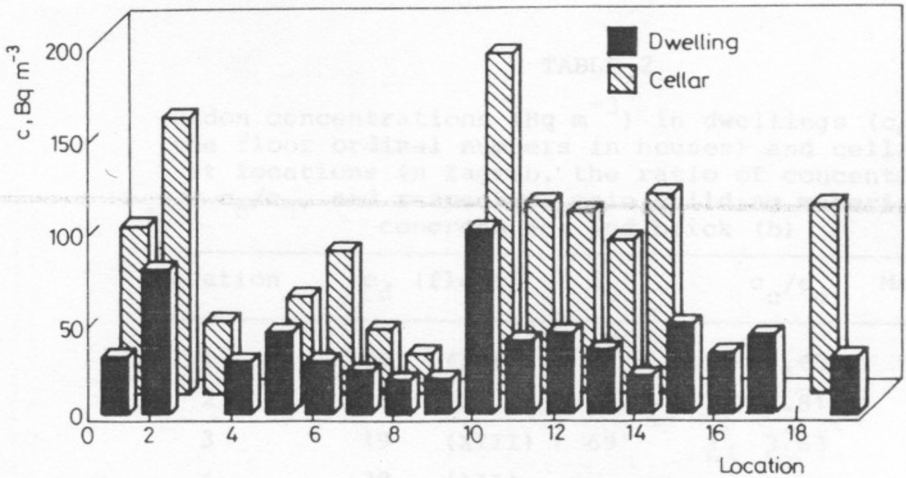

Fig. 1. Radon concentration (c) in shelters or cellars (▨) and dwellings (■) versus ordinal numbers of the locations in Osijek

where the detector parameters were a = 10.79 and b = -7.05. So the F values of 0.58, 0.51, 0.56, in cellars, and 0.52, 0.48, 0.46, in dwellings were obtained at locations 6, 8, 10, respectively.

Statistical errors of the track counting method were determined by experiments with ten LR-115 (filtered) detectors exposed to air in the same room over two months. The mentioned processing of the films gave the average track density, D_o = 0.237 tr $cm^{-2}d^{-1}$, and standard deviation, σ = 0.0263, or the respective variation coefficient, $V(D_o) = \sigma/D_o$ = 11.1%. The relative error of the detector sensitivity coefficient was 1.4% and a total relative error of the track etching method was near 19%.

Indoor radon concentrations, measured in cellars (shelters) of Zagreb (Table 2, Fig. 2), had the arithmetic average value of 104 Bq m^{-3}, with a standard de-

TABLE 2

Radon concentrations (Bq m^{-3}) in dwellings (c_d, with the floor ordinal numbers in houses) and cellars (c_c) at locations in Zagreb, the ratio of concentrations c_c/c_d, and respective main building materials: concrete (c) and brick (b)

Location	c_d	(floor)	c_c	c_c/c_d	Material
1	19	(IV)	31	1.63	c
2	26	(I)	47	1.81	b, c
3	19	(XIII)	69	3.63	b, c
4	38	(III)			b, c
5	47	(III)	36	0.77	b, c
6	26	(IV)	106	4.08	b, c
7	32	(II)	150	4.69	b, c
8	44	(II)	53	1.21	b, c
9	19	(II)	44	2.32	c
10	36	(III)	65	1.81	c
11	24	(IV)	33	1.38	c
12	22	(VI)	72	3.27	c
13	17	(III)	381	22.41	c
14	10	(III)	150	15.00	b, c
15	42	(X)	450	10.71	c
16	15	(II)	47	3.13	b, c
17	32	(III)			c
18	29	(III)	32	1.10	b
19	38	(II)	64	1.68	b, c
20	36	(IV)	93	2.58	c
21	15	(III)	133	8.87	b, c
22	17	(III)	69	4.06	c
23			54	2.35	c

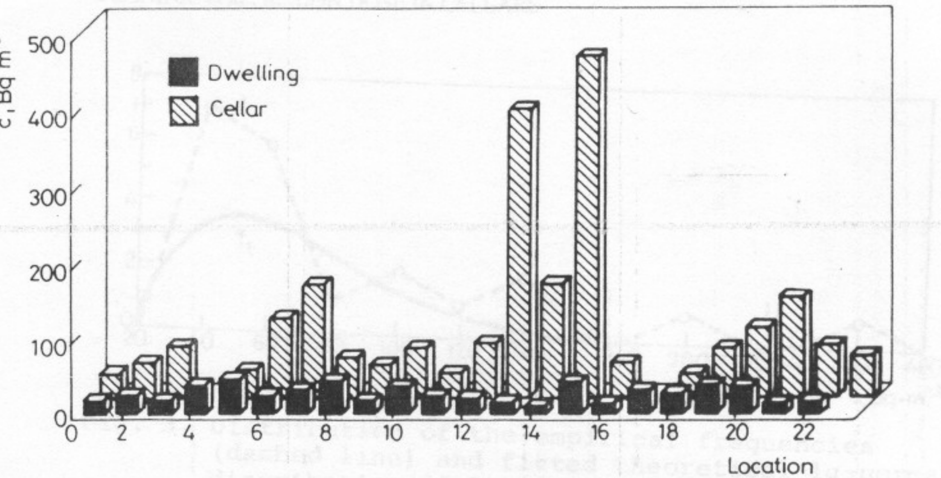

Fig. 2. Radon concentration (c) in shelters or cellars (▧) and dwellings (■) versus ordinal numbers of the locations in Zagreb

viation of (108), in cellars, and the geometric one of 75 Bq m^{-3} (111), but the respective average values in the dwellings were 27 (10) and 25 (11) Bq m^{-3}.

Considering the mentioned arithmetic means and standard deviations of radon concentration, estimated monthly exposures in dwellings and cellars of Zagreb were $(1.94 \pm 0.72) \times 10^4$ Bq h m^{-3} and $(7.45 \pm 7.78) \times 10^4$ Bq h m^{-3}, respectively.

The arithmetic mean of the ratios of radon concentrations in cellars (c_c) to the ones in dwellings (c_d) was 2.77, with a standard deviation of 5.60.

The somewhat higher mean of the concentration ratios (c_c/c_d) in Zagreb (2.77) than in Osijek (2.31) could be explained by means of the building materials, because more concrete was used in construction of houses in Zagreb (e.g. as an isolation between cellar and floors); also the houses in Zagreb were one or two

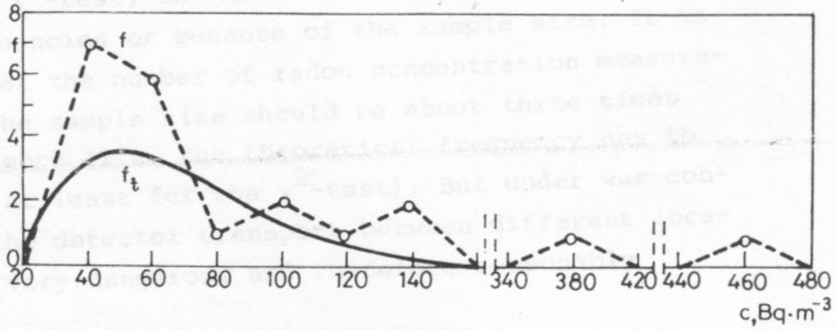

Fig. 3. Distribution of the empirical frequencies (dashed line) and fitted theoretical lg-normal distribution (full line) versus radon concentration (c) in cellars (shelters) of Zagreb grouped in classes with the width of 20 Bq m^{-3}

floors higher than the ones in Osijek, on the average. Generally, higher radon concentrations in cellars than in dwellings indicated that the main radon sources (radium) were in the soil. A similar conclusion could be ascribed to locations 13 and 15 in Zagreb, and elsewhere, with high radon concentrations in cellar.

The frequency distribution of radon concentration in cellars (shelters) of Zagreb, grouped in classes (Fig. 3), had the modal classe between the boundaries of 30 and 50 Bq m^{-3}.

Because the emprical frequency distribution in Fig. 3 was like the lg-normal distribution, this one was fitted to the empirical distribution (omitting two extremely large values of c_c, Table 2) and the χ^2-test for the theoretical and empirical frequencies was performed. Since the calculated value of χ^2 was 7.7 and larger than the theoretical one (χ_o^2=6.0, for a significance level of 0.05 and degrees of freedom of 2), one could not conclude that the empirical distribution belonged to the lg-normal distribution.

By this χ^2-test, the main difficulties appeared by small frequencies or because of the sample size. It is evident that the number of radon concentration measurements or the sample size should be about three times larger or more (i.e. the theoretical frequency has to be near 5 at least for the χ^2-test). But under war conditions, the detector transport between different locations was very dangerous and therefore reasonably limited.

The effective dose equivalent (H) of radon and its progeny was calculated in the following way[1]:

$$H = c\,(d + d_e F) \quad , \qquad (3)$$

where the effective dose equivalent conversion factors were d_e = 80 μSv/y per Bq/m^3 and d = 0.33 μSv/y per Bq/m^3 (Ref. (3)). Here the radon concentration (c) was the average concentration measured by the R detector.

Under the worst conditions, assuming an occupancy factor of 100% in the shelters during the war and F as the average of the measured equilibrium factors at the locations mentioned (6, 8, 10), inhabitants of Osijek have received the effective dose equivalent of 4.1 mSv per year, on the average, or from 1 to 8.2 mSv per year (the war has continued for ten months in Osijek, but it is not yet quite finished in Croatia). Because the conversion factors for younger populations were larger for a factor of 1.5 (Ref. (4)), children have received doses of up to 12.3 mSv per year.

Supposing inhabitants of Zagreb had the occupancy factors of 30% in shelters and 70% in dwellings, the assessed effective dose equivalent was 2.6 mSv/y, on the average. This dose value was by a factor of 2.36 larger than the effective dose equivalent for Zagreb's dwellings with a 100% occupancy factor. The received doses could reach significant values considering the inhabitant's health particularly the respiratory tracts well as the genetic effects. The calculated dose for children is by a factor of 12 higher than the recommended effective dose equivalent limit per year for radon and its daughters (1 mSv)[4].

CONCLUSION

Radon concentration in shelters (cellars) and dwellings of Osijek, measured by a silicon detector, had the arithmetic average values of 92, with the standard deviation of (44), and 40 (22) Bq m^{-3}, but they were 104 (108) and 27 (10) Bq m^{-3}, in Zagreb, respectively. Estimated monthly radon exposures in dwellings and cellars of Osijek or Zagreb were $(2.88 \pm 1.58) \times 10^4$ and $(6.62 \pm 3.17) \times 10^4$, respectively, or $(1.94 \pm 0.72) \times 10^4$ and $(7.45 \pm 7.78) \times 10^4$ Bq h m^{-3}. The arithmetic mean of the ratios of radon concentrations in cellars to the ones in dwellings of Osijek was 2.31, with a standard deviations of (1.06) and 2.77 (5.60) in Zagreb. The LR-115 nuclear track detector was used for additional and comparing Rn concentration measurements as well as equilibrium factor determinations. The relative statistical error of the track counting method was near 19%, while the error of the silicon detector was about 20%. The distribution of the empirical frequencies of the grouped radon concentrations in cellars (shelters) of Zagreb was like the lg-normal distribution, but the χ^2-test did not confirm it; a larger sample of the concentration measurements could give a clearer answer by the statistical test.

Under the war conditions (occupancy factor in shelters of 100%), inhabitants of Osijek have received the effective dose equivalent of 4.1 mSv y^{-1}, on the average, or from 1 to 8.2 mSv y^{-1}. Inhabitants of Zagreb, with occupancy factors of 30% and 70% in shelters and dwellings, respectively, have received an average dose of 2.6 mSv y^{-1}.

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