Abstract

Indoor air concentrations of radon and radon short-lived decay products, equilibrium factor, unattached fraction of radon short-lived decay products ($f_{un}$), relative humidity and temperature have been measured in Slovenian schools, with an emphasis on $f_{un}$ as the crucial parameter in dose assessment. $f_{un}$ ranged from 0.03 to 0.21. Dose conversion factors, based on these values, exceeded 5 mSv/WLM, the value recommended by ICRP-65, in all schools.

Key words: radon unattached fraction, dose conversion factors.

Introduction

Radon is an $\alpha$-radioactive noble gas originating in the Earth's crust, from where it travels toward the surface by diffusion and, mostly by being transported by thermal waters or carrier gases such as methane, helium and carbon monoxide. There are three isotopes: $^{222}$Rn (radon with a half-life $\tau = 3.8$ days) originates from $^{226}$Ra in the $^{238}$U decay chain; $^{220}$Rn (thoron, $\tau = 56$ seconds) from $^{224}$Ra in the $^{232}$Th decay chain; and $^{219}$Rn (actinon, $\tau = 3.9$ seconds) from $^{223}$Ra in the $^{228}$U decay chain. Only the $^{222}$Rn isotope (hereafter simply called radon) has a half-life long enough to appear in indoor air (both in homes and at workplaces) at activity levels potentially hazardous for our health. Radon further decays ($\alpha$, $E_{\alpha} = 5.5$ MeV) into its short-lived decay products (RnDP): $^{218}$Po ($\alpha$ decay, $\tau = 3.1$ min, $E_{\alpha} = 6.0$ MeV), $^{214}$Pb ($\beta-\gamma$ decay, $\tau = 26.8$ min), $^{214}$Bi ($\beta-\gamma$ decay, $\tau = 19.9$ min) and $^{214}$Po ($\alpha$ decay, $\tau = 164$ $\mu$s, $E_{\alpha} = 7.7$ MeV). Short-lived decay products originate as positive ions, which soon recombine with air molecules to form clusters, with an activity median aerodynamic diameter (AMAD) of 0.8 nm (called the unattached fraction of RnDP). Later, some of them attach to dust particles and water droplets to form aerosols with AMAD around 200 nm (called the attached fraction of RnDP). In calm and clean air, a radioactive equilibrium between Rn and RnDP may be reached in about three hours, i.e., from 1 Bq of Rn, 1 Bq of each RnDP is generated. In reality equilibrium is never reached because of air movement and plate-out of aerosols on walls and floors. The equilibrium factor, $F$, measures the state of radioactive equilibrium, and is in the range 0.40 – 0.50 in indoor air.

When breathing in air contaminated by Rn and RnDP, Rn is inhaled and exhaled, and only a minor fraction decays in the lungs. On the other hand, RnDP appear in the form of clusters and aerosols which are deposited on the walls of airways in the mouth, nose and lungs, where they further decay and damage the nearby tissue. For this reason, we are mainly concerned about RnDP (mostly $\alpha$-active $^{218}$Po and $^{214}$Po because of high $\alpha$-energies) and not about Rn which contributes only about 5% to the lung dose, although we use the general notion of radon dosimetry.

It is relatively simple to measure long-term average Rn concentration in air by exposing track-etched detectors. In contrast, there is no commercially available device to obtain long-term average RnDP concentration. Therefore, it is general practice in radon dosimetry to measure Rn and then to translate its concentrations into RnDP concentration using $F = 0.40$, as recommended by ICRP-65 methodology. The exposure to Rn and/or RnDP is expressed in an old though convenient unit, WLM (working-level-month). 1 WLM is the exposure received by 170 hours breathing in air with an activity concentration of RnDP of 1 WL,
which is defined as $^{218}\text{Po}$, $^{214}\text{Bi}$, $^{214}\text{Pb}/^{214}\text{Po}$ in radioactive equilibrium ($F = 1$) with 100 pCi/L ($3700 \text{ Bqm}^{-3}$) of $^{222}\text{Rn}$, resulting in an alpha energy concentration of $1.3 \times 10^6 \text{ MeV/L}$. The effective dose according to ICRP-65, $E_{65}$, is then calculated using the equation:

$$E_{65} = \frac{C_{\text{Rn}} \times F}{3700} \times \frac{t}{170} \times DCF$$ (1)

$C_{\text{Rn}}$ is average Rn concentration for the time period $t$ (in hours) spent by a person in the room surveyed. $DCF$ is a dose conversion factor, recommended by ICRP-65 as 5 mSv/WLM.

In a recently proposed, refined dosimetric approach based on a new lung model $^{5,5}$, $DCF$ is not taken from ICRP-65 but is rather expressed through the fraction of unattached RnDP, $f_{\text{un}}$, by:

$$DCF_m = 101 \times f_{\text{un}} + 6.7 \times (1 - f_{\text{un}})$$ (2)

for mouth breathing,

and

$$DCF_n = 23 \times f_{\text{un}} + 6.2 \times (1 - f_{\text{un}})$$ (3)

for nasal breathing.

The dose conversion factor for a person, $DCF$, is then composed of $DCF_m$ and $DCF_n$ by taking into account the fraction of mouth ($x$) and nasal ($1 - x$) breathing, i.e.,

$$DCF = x \times DCF_m + (1 - x) \times DCF_n.$$ (4)

If $DCF$ is used instead of 5 mSv/WLM, the resulting effective dose is denoted by $E_{\text{un}}$, to be differentiated from $E_{65}$:

$$E_{\text{un}} = \frac{C_{\text{Rn}} \times F}{3700} \times \frac{t}{170} \times DCF$$ (5)

In the Slovenian Radon Programme, radon was surveyed in 890 elementary and high schools in the period from 1992–94. $^{6-16}$ In 78 cases, where indoor air radon concentrations exceeded the national radon limit of 400 Bqm$^{-3}$, additional and more intensive investigations were carried out and effective doses of teachers and students were calculated according to ICRP-65 methodology,$^{3}$ using equation (1). In 15 buildings radon problem has been mitigated and doses of personnel successfully reduced to an acceptable level.

In order to check the role of the unattached fraction of RnDP in radon dosimetry, i.e., to compare $E_{\text{un}}$ to $E_{65}$, in the period 1998–2003, we carried out 7–15 day continuous measurements of indoor air concentrations of radon and radon short-lived decay products, equilibrium factor and unattached fraction of radon short-lived decay products in 30 Slovenian schools. Air relative humidity and temperature were also monitored, as two parameters affecting $f_{\text{un}}$. In this paper, the influence of environmental parameters and of the working regime on the measured quantities, with emphasis on $f_{\text{un}}$ and consequently on $E_{\text{un}}$ received by the personnel, have been sought and commented on with regard to the previously obtained $E_{65}$ values.

**Experimental**

In the study, portable SARAD EQF3020 and EQF3020-2 devices (manufactured by SARAD, Dresden, Germany) have been used. They measure concentrations of radon ($C_{\text{Rn}}$) and radon short-lived decay products ($C_{\text{RnDP}}$) and equilibrium factor ($F$), as well as air temperature ($T$) and relative air humidity ($RH$). $^{23}$ The sampling and analysing frequency is once in two hours. A filter separates aerosols with AMAD below 10 nm from those above, enabling measurements of unattached ($f_{\text{un}}$) and attached fractions of RnDP. Alpha spectrometry is used to detect $^{218}\text{Po}$ and $^{214}\text{Po}$, based not on their a-energies but on the difference in their half-lives, by measuring the total a-activity on the filter at different appropriately selected times.$^{24}$ A device has been operated for 7-15 days in one or several rooms of the selected school.

The instruments were calibrated by the manufacturer at the time of purchase, and have since then been checked by the manufacturer every two years. In addition, they have been regularly included in the intercomparison experiments organized annually by the Slovenian Nuclear Safety Administration at the Ministry of Environment and Spatial Planning.$^{25}$

**Results and discussion**

**Temporal variation of the measured parameters and some of their relationships**

Figure 1 shows time variations of: a) concentration of radon ($C_{\text{Rn}}$) and equilibrium factor ($F$), b) concentration of radon short-lived decay products ($C_{\text{RnDP}}$) and unattached fraction of short-lived radon decay products ($f_{\text{un}}$), and c) relative air humidity ($RH$) and air temperature ($T$), as recorded during a measurement in the s-MO-S3-01 school. $C_{\text{Rn}}, C_{\text{RnDP}}$, and $F$ show diurnal fluctuations,$^{1,11,12}$ with maxima...
much more pronounced in school s-MO-S3-01 than in school s-SM-S2-12 this reduction was far less, and to below 100 Bqm$^{-3}$ during working hours (Figure 1), in school s-SM-S2-12 this reduction was far less, and values remained above 1000 Bqm$^{-3}$ during the whole day (Figure 2). Also daily fluctuations of $F$ and $f_{un}$ are much more pronounced in school s-MO-S3-01 than in school s-SM-S2-12.

Figure 3a shows an exponential decrease of $f_{un}$ with increasing $F$, as observed also in other experiments. Figure 3b shows a poor positive correlation of $f_{un}$ with $HR$, and Figure 3c, a weak negative one with $T$. These relationships are very complex and their interpretation is beyond the scope of this paper because no data on the number of aerosol particles in air and its dependence on the working regime is available. In addition, $RH$ and $T$ ranges (which are related) were too narrow to cause apparent changes in $f_{un}$, because the enhancement of RnDP neutralisation rate due to an increase of $RH$ from 20 to 30% is insignificant.

Comparison of $E_{65}$ and $E_{un}$ effective doses

For each school, average values of $C_{Rn}$ and $f_{un}$ were calculated for working hours (7–14 h) for the whole period of measurement in the school. Values are collected in Table 1. $f_{un}$ values range from 0.03 to 0.21, to be compared with the value of 0.03 implemented in the ICRP-65 methodology for calculating $E_{65}$. $E_{65}$ doses were calculated by using equation (1), and $E_{un}$ by equations (2) – (5), assuming 80% mouth and 20% of nasal breathing for a teacher. In addition to $DCF_{un}$, $DCF_{un}$ and

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**Figure 1.** Temporal variations of the parameters measured in the s-MO-S3-01 school during the period January 18–27, 2000: a) concentration of radon ($C_{Rn}$) and equilibrium factor ($F$), b) concentration of radon short-lived decay products ($C_{RnDP}$) and fraction unattached of short-lived radon decay products ($f_{un}$), c) relative indoor air humidity ($RH$) and indoor air temperature ($T$).

**Figure 2.** Temporal variation of the parameters measured in the s-SM-S2-12 school during the period January 18–27, 2000: a) concentration of radon ($C_{Rn}$) and equilibrium factor ($F$), b) concentration of radon short-lived decay products ($C_{RnDP}$) and unattached fraction of short-lived radon decay products ($f_{un}$), c) relative indoor air humidity ($RH$) and indoor air temperature ($T$).
DCF<sub>f</sub> values, Table 1 also shows the \( E_{un}/E_{65} \) ratio for each school. It is immediately evident that the ratio is higher than 1 for all schools and that the annual effective doses estimated for the school personnel according to the ICRP-65 methodology without taking into account the unattached fraction of RnDP may therefore be highly underestimated. It would thus be advisable to use \( E_{un} \) instead of \( E_{65} \) in order to ensure being on the safe side from the radiation protection point of view. Referring to Figure 3a, we see compensating effects of \( f_{un} \) and \( F \): an enhanced \( F \) would result in higher exposure, but the concomitant lower \( f_{un} \) will reduce it.

At present the devices to monitor \( f_{un} \) are sophisticated and expensive, and we are far from being able to use them simultaneously at a number of places for long periods of time, as required for a massive radon dosimetry. Therefore, ICRP-65 methodology based on exposing etched track detectors all the year round will still remain in general practice in the near future, and \( f_{un} \)-based radon dosimetry will be used for scientific purposes only.

![Figure 3](image_url)

**Figure 3.** Dependence of \( f_{un} \) – the fraction of unattached short-lived radon decay products – on: a) \( F \) – equilibrium factor, b) \( RH \) – relative indoor air humidity and c) \( T \) – indoor air temperature, for the measurements in the s-MO-S3-01 school during the period January 18–27, 2000.

### Table 1.

<table>
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<th>School code</th>
<th>measuring period</th>
<th>( C_{un}^{*} ) Bqm–3</th>
<th>( f_{un} )</th>
<th>( DCF_{m} )</th>
<th>( DCF_{n} )</th>
<th>( DCF_{c} )</th>
<th>( E_{un}/E_{65} )</th>
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</table>

**Conclusions**

Measurements of \( f_{un} \) in 30 Slovene schools have shown values between 0.03 and 0.21. Dose conversion factors, \( DCF \), for mouth (m) and nasal (n) breathing were calculated and the combined (c) values for all schools obtained, assuming \( DCF_{m} = 0.80 \times DCF_{m} + 0.20 \times DCF_{n} \). By including \( DCF = 5 \) mSv/WLM and \( DCF = DCF_{c} \), effective doses \( E_{65} \) and \( E_{un} \) respectively, were calculated. The ratio of \( E_{un}/E_{65} \) ranged from 1.79 to 4.63, being higher than 1 for all schools. Thus, the doses calculated according to ICRP-65 methodology without taking into account the unattached fraction of RnDP were always underestimated. Therefore, whenever the equipment is available, it is advisable to consider the measured data on the unattached fraction of short-lived radon decay products when arriving at dose estimates.

**Acknowledgements**

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Povzetek

V izbranih šolah s povišano koncentracijo radona v Sloveniji smo merili koncentracijo radona (C_{radon}) in radonovih krakoživih razpadnih produktov (C_{radon}), ravenotežni faktor (F), delež neveznih radonovih razpadnih produktov (f_{un}), zračni tlak (P), relativno vlažnost zraka (RH) in temperaturo zraka (T). Poseben poudarek je bil na f_{un} in na njegovi odvisnosti od delovnega režima. Vrednosti f_{un} so bile v širokem razponu, od 0,03 do 0,21. Z uporabo novega dozimetrijskega modela smo na osnovi izmerjenih vrednosti f_{un} izračunali dozne pretvorbene faktorje in ugotovili, da so bili višji od vrednosti 5 mSv/WLM, ki jo priporoča metodologija ICRP-65.