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Mitigation of radon and thoron decay products by filtration

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ABSTRACT

Inhalation of indoor radon (^{222}Rn) and thoron (^{220}Rn) decay products is the most important source of exposure to ionizing radiation for the human respiratory tract. Decreasing ventilation rates due to energy saving reasons in new buildings suggest additional active mitigation techniques to reduce the exposure in homes with high radon and thoron concentrations but poor ventilation. Filtration techniques with HEPA filters and simple surgical mask material have been tested for their potential to reduce the indoor exposure in terms of the total effective dose for mixed radon and thoron indoor atmospheres. The tests were performed inside an experimental room providing stable conditions.

Filtration (at filtration rates of 0.2 h^{-1} and larger) removes attached radon and thoron decay products effectively but indoor aerosol as well. Therefore the concentration of unattached decay products (which have a higher dose coefficient) may increase. The decrease of the attached decay product concentrations could be theoretically described by a slowly decreasing exponential process. For attached radon decay products, it exhibited a faster but weaker removal process compared to attached thoron decay products (−70% for attached radon decay products and −80% for attached thoron decay products at a filtration rate of 0.5 h^{-1} with an HEPA filter). The concentration of unattached thoron decay products increased distinctly during the filtration process (+300%) while that of unattached radon decay products rose only slightly though at a much higher level (+17%). In the theoretical description these observed differences could be attributed to the different half-lives of the nuclides. Considering both effects, reduced attached and increased unattached decay product concentrations, filtration could significantly decrease the total effective dose from thoron whereas the overall effect on radon dose is small. A permanent filtration is recommended because of the slow decrease of the thoron decay product concentrations.

1. Introduction

It is well understood that a major part of the exposure to ionizing radiation is attributed to the inhalation of the decay products of the noble gasses radon (^{222}Rn) and thoron (^{220}Rn) indoors (UNSCEAR, 2006; WHO, 2009). Radon, which enters indoor space mainly from the soil below the building, has been in the focus of radiation protection research for several decades. Thoron, however, has been gaining attention only during the last few years. Increased thoron concentrations have been measured e.g. in Italian tuff and pozzolana buildings (Sciocchetti et al., 1992), Japanese traditional mud houses (Doi et al., 1992; Guo et al., 1992), and Chinese traditional clay dwellings (Shang et al., 2005; Tschiersch et al., 2007); the source of thoron in these buildings is the building material. A suitable quantity for specifying the exposure of people to the gasses and their decay products is the potential alpha energy concentration (*PAEC*), which is the emitted alpha energy of all short-lived decay product atoms present per unit volume of air. The *PAEC* from a certain activity of thoron decay products is larger than that from the same activity of radon decay products by a factor of 14, mainly because of the longer half-lives of the nuclides. Therefore, the contribution of thoron and its decay products to the inhalation exposure was of about the same level as that of radon in some of the above mentioned dwellings (Tschiersch et al., 2007) despite their smaller concentration.

The mitigation of the inhalation dose caused by thoron decay products therefore can be as important an issue as that of the inhalation dose caused by radon. Among various mitigation approaches such as ventilation or sealing the foundation of houses, filtration has a relatively long history in mitigating the inhalation exposure from radon decay products. A variety of methods such as electro-filter (Jonassen and McLaughlin, 1985), air cleaner with a mechanical filter (Kojima et al., 1992), high efficiency particulate air filter (HEPA filter) (Kranrod et al., 2009; Rajala et al., 1985; Yasuoka et al., 2009) had been tested in the past. However, no distinct results for a reduction of the inhalation dose could be found, for which reason the U.S. Environmental Protection Agency

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does not recommend air filtration as a measure of radon mitigation (EPA, 2009). In the context of increasing reports on enhanced thoron concentrations, this study explores the mitigation potential of the mixed dose from radon and thoron decay products using filters (HEPA and surgical mask type), and discriminates and analyzes the different responses and behaviors in the same filtration system. For this purpose, measurement results, which were obtained during filtration experiments, are compared with model calculations.

2. Materials and methods

2.1. Experimental set-up

Measurements were carried out in an experimental model room made of thoron-exhaling mudbricks (Tschiersch and Meisenberg, 2010). It features a volume of 7.1 m^3 and a surface of 21 m^2; its surface-to-volume-ratio of 3 m^{-1}, which is the relevant parameter for the calculation of the deposition rate, is in the range of inhabited rooms (2.5–8.4 m^{-1}, average 4.9 m^{-1}, Knutson et al., 1992). Therefore, measurement results from the experimental room can be transferred to real dwellings; possible differences are discussed below.

The air exchange with thoron-free outdoor air can be adjusted by opening or closing its two windows and one door. The temperature was about 20 °C and the humidity was about 50% during the measurements.

A time-resolving working level monitor (Tracerlab GmbH, Germany) along with a modified working level monitor, which was installed with a wire screen of mesh 635, were applied in the experimental room, working continuously to record the *PAEC* of total (attached and unattached radon/thoron decay products) and the unattached decay products, respectively. The detailed working principle of the two monitors is illustrated comprehensively (Tschiersch et al., 2007; Meisenberg and Tschiersch, 2009). Changes of the airborne decay product concentrations which occur much faster than the half-lives of the nuclides (i.e. faster than about 30 min for radon and than about 10 h for thoron) cannot be traced, a shortcoming which is common for all detectors of that type (Bigu et al., 1984).

Aerosol number concentrations were measured with a condensation particle counter (3022A, TSI, USA). It featured a lower cut-off diameter of 7 nm and an air flow rate of 18 L h^{-1}.

A membrane pump combined with an HEPA filter (high efficiency particulate air filter, GEA mbH, Germany) and a needle valve was used to filter the air from the experimental room under the filtration rates (h^{-1}) of 0.2, 0.3, 0.5, and 0.8, respectively; such filtration rates can also be obtained by household air cleaners. The filtration system was connected to the experimental room in a closed loop such that the air was taken out of the room at one side and led back at the opposite side; pump and filter were positioned outside the room. A surgical mask (Henan XinXiang YuAn Medical Hygienic Material Co. Ltd., China) directly attached to a small encased fan (ø 10 cm), which was placed inside the room, was used as a cheap and widely applicable alternative to get a comparison to the HEPA filter. The filtration rate of this arrangement was determined to be 3 h^{-1}. Before each filtration period, the air exchange rate was kept at 0.1 h^{-1} (door and windows closed) for several days to let the radon and thoron decay products reach equilibrium and then the pump was started to filter the air for around 4 days with the air exchange rate left unchanged. After stopping filtration, the door and windows were opened completely for a couple of hours in order to exchange air with the ambient environment, and then they were closed again to wait for new equilibrium and stable concentration for the next filtration. A blank experiment without filtration (control case) was also performed. The radon concentration during the experiments was about 200 Bq m^{-3} and did not change significantly during filtration. Without filtration, the thoron concentration was about 800 Bq m^{-3} directly at the walls and below 20 Bq m^{-3} in the middle of the room; during filtration the thoron concentration in the middle of the room increased to about 40 Bq m^{-3} whereas that at the wall decreased slightly.

The air flow rate through the HEPA filter (1.4–6 m^3 h^{-1}) was measured with a gas meter and a stop watch. The air flow rate through the surgical mask (23 m^3 h^{-1}) was calculated from the air velocity at several positions in front of the mask, which was measured with a hot-sphere anemometer. The filtration rates were calculated as these air flow rates divided by the volume of the room.

2.2. Theoretical considerations

The concentration and temporal behavior of the airborne radon and thoron decay products are governed by several sources and sinks: Unattached ^{214}Pb and ^{212}Pb originate from the radioactive decay of radon and thoron, respectively (assuming that the nuclides ^{218}Po and ^{216}Po in between are in equilibrium to the gasses because of their relatively short half-lives), and subsequently ^{214}Bi and ^{212}Bi originate from the decay of these nuclides. Attached decay products result from the attachment of unattached decay products to aerosol particles, attached ^{214}Bi and ^{212}Bi additionally from the radioactive decay of already attached ^{214}Pb and ^{212}Pb. Sinks of the airborne decay products are radioactive decay, air exchange, deposition onto surfaces, and, only for unattached ones, attachment to aerosol particles. Filtration, which is highlighted in this work, is another potential sink. These sources and sinks yield the following set of differential equations for the concentrations c of the two nuclides in each decay chain (index 1 for ^{214}Pb/^{212}Pb, 2 for ^{214}Bi/^{212}Bi) and in the two states in which they occur (index u for unattached, a for attached):

$$\frac{dc_{1u}}{dt} = \lambda_1 \cdot c_{gas} - (\lambda_1 + aer + \delta_u + \beta Z + \varphi) \cdot c_{1u} \quad (1)$$

$$\frac{dc_{1a}}{dt} = \beta Z \cdot c_{1u} - (\lambda_1 + aer + \delta_a + \varphi) \cdot c_{1a} \quad (2)$$

$$\frac{dc_{2u}}{dt} = \lambda_2 \cdot c_{1u} - (\lambda_2 + aer + \delta_u + \beta Z + \varphi) \cdot c_{2u} \quad (3)$$

$$\frac{dc_{2a}}{dt} = \lambda_2 \cdot c_{1a} + \beta Z \cdot c_{2u} - (\lambda_2 + aer + \delta_a + \varphi) \cdot c_{2a} \quad (4)$$

where λ_i is the decay constant of the respective nuclide, c_{gas} is the concentration of radon or thoron (averaged over the volume of the room), aer is the air exchange rate, δ is the deposition rate, β is the rate of attachment to aerosol particles, Z is the aerosol concentration, φ is the filtration rate. Meisenberg and Tschiersch (2011) discussed these differential equations in detail.

When filtration is started, the temporal change of the decay product concentrations is described by the general solution of the differential equations. However, not only the filtration rate φ changes from $\varphi = 0$ at $t = 0$ to its respective value but also the aerosol concentration features a time dependence in the course of filtration. In the following analytical solution of the differential equations, the aerosol concentration is considered to adopt its new value instantaneously at the beginning of the filtration. Also the concentrations of the decay products which appear in the right-hand sides of the solutions are assumed to change instantaneously. A continuous time dependence would make the solution much more complex; it is discussed later.

$$\begin{aligned} c_{1u}(t) = {} & \frac{\lambda_1 \cdot c_{gas}}{\lambda_1 + aer + \delta_u + \beta Z_{post} + \varphi} \\ & + \left(\frac{\lambda_1 \cdot c_{gas}}{\lambda_1 + aer + \delta_u + \beta Z_{pre}} - \frac{\lambda_1 \cdot c_{gas}}{\lambda_1 + aer + \delta_u + \beta Z_{post} + \varphi} \right) \\ & \times exp\left(-\left(\lambda_1 + aer + \delta_u + \beta Z_{post} + \varphi \right) t \right) = c_{1u\,post} \\ & + \left(c_{1u\,pre} - c_{1u\,post} \right) \times exp\left(-\left(\lambda_1 + aer + \delta_u + \beta Z_{post} + \varphi \right) t \right) \end{aligned} \quad (5)$$

$$c_{1a}(t) = \frac{\beta Z_{post} \cdot c_{1u\ post}}{\lambda_1 + aer + \delta_a + \varphi} + \left(\frac{\beta Z_{pre} \cdot c_{1u\ pre}}{\lambda_1 + aer + \delta_a} - \frac{\beta Z_{post} \cdot c_{1u\ post}}{\lambda_1 + aer + \delta_a + \varphi}\right) \times exp(-(\lambda_1 + aer + \delta_a + \varphi)t) = c_{1a\ post} + \left(c_{1a\ pre} - c_{1a\ post}\right) \times exp(-(\lambda_1 + aer + \delta_a + \varphi)t) \quad (6)$$

$$c_{2u}(t) = \frac{\lambda_2 \cdot c_{1u\ post}}{\lambda_2 + aer + \delta_u + \beta Z_{post} + \varphi} + \left(\frac{\lambda_2 \cdot c_{1u\ pre}}{\lambda_2 + aer + \delta_u + \beta Z_{pre}} - \frac{\lambda_2 \cdot c_{1u\ post}}{\lambda_2 + aer + \delta_u + \beta Z_{post} + \varphi}\right) \times exp\left(-\left(\lambda_2 + aer + \delta_u + \beta Z_{post} + \varphi\right)t\right) = c_{2u\ post} + \left(c_{2u\ pre} - c_{2u\ post}\right) \times exp\left(-\left(\lambda_2 + aer + \delta_u + \beta Z_{post} + \varphi\right)t\right) \quad (7)$$

$$c_{2a}(t) = \frac{\lambda_2 \cdot c_{1a\ post} + \beta Z_{post} \cdot c_{2u\ post}}{\lambda_2 + aer + \delta_a + \varphi} + \left(\frac{\lambda_2 \cdot c_{1a\ pre} + \beta Z_{pre} \cdot c_{2u\ pre}}{\lambda_2 + aer + \delta_a} - \frac{\lambda_2 \cdot c_{1a\ post} + \beta Z_{post} \cdot c_{2u\ post}}{\lambda_2 + aer + \delta_a + \varphi}\right) \times exp(-(\lambda_2 + aer + \delta_a + \varphi)t) = c_{2a\ post} + \left(c_{2a\ pre} - c_{2a\ post}\right) \times exp(-(\lambda_2 + aer + \delta_a + \varphi)t) \quad (8)$$

Indices pre and post denote the values of the time dependent quantities before and during the filtration.

The temporal behavior of the concentrations of the decay products in the case of a continuous exponential decrease of the aerosol concentration was calculated by solving the differential equations using the computer algebra software Maple 7 (Waterloo Maple Inc., Canada) with

$$Z(t) = Z_{post} + \left(Z_{pre} - Z_{post}\right) \exp(-\lambda_Z t) \quad (9)$$

Also $c_{1u}(t)$, $c_{1a}(t)$, and $c_{2u}(t)$ as they appear as independent variables in the right-hand sides of the latter differential equations were used with their continuous time-dependence.

The potential alpha-energy concentration of radon and thoron decay products respectively is the sum of the contributions c_1 and c_2 of the two nuclides from the respective decay chain:

$$PAEC = k_1 c_1 + k_2 c_2 \quad (10)$$

with $k_1 = 2.86$ nJ/Bq and $k_2 = 2.10$ nJ/Bq for ^{214}Pb and ^{214}Bi as the radon decay products and $k_1 = 69.1$ nJ/Bq and $k_2 = 6.56$ nJ/Bq for ^{212}Pb and ^{212}Bi as the thoron decay products (Nero, 1988). ^{218}Po is another nuclide from the decay chain of radon and contributes to the *PAEC* with a small weighting factor of 0.58 nJ/Bq, i.e. 10% of the total *PAEC* in equilibrium; therefore it is not considered here.

Values for the decay constants λ_i of the nuclides, the coefficients of attachment to aerosol particles β, and the deposition velocities v_{dep} are published in literature. The deposition rates δ can be calculated with the surface S of the room and its volume V as

$$\delta = v_{dep} \cdot S / V \quad (11)$$

Values of these quantities are presented in Table 1.

Table 1
Values of the quantities which determine the sources and sinks of the nuclides in the radon and thoron decay chain besides filtration. Deposition rates δ are given for the experimental room.

Quantity	Comment	Decay chain of		Reference
		Radon	Thoron	
Decay constant λ_i [h^{-1}]	i = 1	1.55	$6.5 \cdot 10^{-2}$	Firestone et al., 1996
	i = 2	2.09	$6.9 \cdot 10^{-1}$	Firestone et al., 1996
Attachment coefficient β [$cm^3\ h^{-1}$]		$5 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	Meisenberg and Tschiersch, 2011; Porstendörfer, 1994
Attachment rate βZ [h^{-1}]	Before filtration, at $Z = 2000$ cm^{-3}	$1 \cdot 10^{1}$	6	
	During filtration, at $Z = 600$ cm^{-3}	3	2	
Deposition velocity v_{dep} [$cm\ s^{-1}$]	Unattached	$2 \cdot 10^{-1}$	$8 \cdot 10^{-3}$	Knutson, 1988; Meisenberg and Tschiersch, 2011
	Attached	$2 \cdot 10^{-3}$	$3 \cdot 10^{-4}$	Knutson, 1988; Meisenberg and Tschiersch, 2011
Deposition rate δ [h^{-1}]	Unattached	$2 \cdot 10^{1}$	$8 \cdot 10^{-1}$	
	Attached	$2 \cdot 10^{-1}$	$3 \cdot 10^{-2}$	

3. Results and discussion

3.1. Theoretical description

Fig. 1 shows the relative temporal behavior of the *PAEC*s of attached radon and thoron decay products during filtration at the employed air exchange rate *aer* of 0.1 h^{-1} and at a typical filtration rate φ of 0.5 h^{-1}. The aerosol concentration is assumed to change from $Z_{pre} = 2000$ cm^{-3} to $Z_{post} = 600$ cm^{-3} as it was observed during measurements in the experimental room at that filtration rate; for its continuous decrease, the decrease rate λ_Z was taken as 1 h^{-1}.

The concentration of the thoron decay products decreases over a period of several hours to about 20% of the original value both in the case of an instantaneous and in that of a continuous decrease of the aerosol concentration; the decrease rate is determined by the long half-lives of the nuclides. The concentration of the radon decay

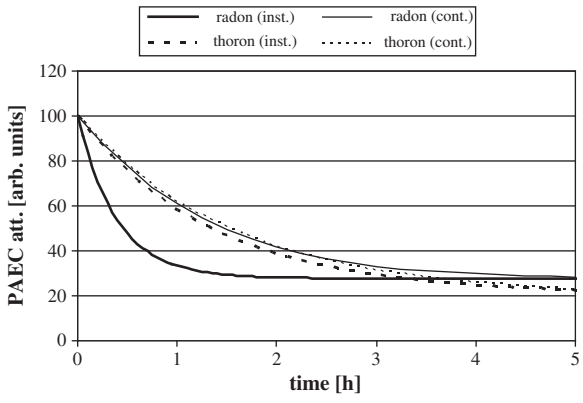

Fig. 1. Theoretically derived behavior of the concentrations of attached radon and thoron decay products during filtration at a rate of 0.5 h^{-1} and started at $t = 0$. The values presented in Table 1 are used for the quantities describing the sinks of the nuclides. Two cases of the time dependence of the aerosol concentration are depicted: its new value is adopted instantaneously at the beginning of filtration (inst.) and the new value is adopted by a continuous exponential decrease of the concentration (cont.).

products features a decrease to its new value of equilibrium of 30%. In contrast to the thoron decay chain, the decrease is slow only in the case of a continuous change of the aerosol concentrations; in the case of an instantaneous change, the radon decay product concentration follows the changed condition quickly within about 1 h because of the shorter half-lives of the nuclides.

The half-lives also cause the different filtration efficiencies: The longer half-lives of the thoron decay products are a less competitive sink compared to the filtration rate. However, the additional sinks such as deposition result in a smaller difference than the strongly different decay constants suggest; especially at greater air exchange rates the filtration efficiencies will converge. In all cases, the newly balanced decay product concentration is based on the equilibrium between continuing production of the decay products from the decaying gas on the one hand and radioactive decay, air exchange, deposition plus filtration on the other hand.

The ratio of the radon decay products ^{214}Pb:^{214}Bi was 1.09 at the beginning and 1.28 at the end of the filtration; the contribution to the *PAEC* of the decay chain changed from 60%/40% to 63%/37%. The respective values for the thoron decay products ^{212}Pb and ^{212}Bi are 1.17 (92.5%/7.5%) and 1.69 (94.7%/5.3%).

Fig. 2 presents the temporal behavior of unattached radon and thoron decay products under the same conditions as above. The values are scaled such that they represent the typical ratio of unattached to attached decay products at the respective aerosol concentration (at $Z_{pre} = 2000\ cm^{-3}$ 20% for radon and 3% for thoron, Meisenberg and Tschiersch, 2011).

Considering relative changes, a significant increase of the concentration of unattached thoron decay products can be seen whereas the concentration of unattached radon decay products does hardly change. During filtration, the filtration of the unattached decay products themselves competes with the smaller aerosol concentrations and thus smaller attachment rates; this causes the distinct difference from the behavior of the attached decay products. Because of the strong other sinks which act on unattached radon decay products (much stronger deposition than of unattached thoron decay products, greater decay constant) the increase is much smaller for unattached radon decay products than for those of thoron. Also with unattached decay products, the steady-state concentration during filtration is that in equilibrium between further production of unattached decay products and the sinks which act on them; these sinks are radioactive decay, air exchange, deposition, attachment to the aerosol particles (now of smaller concentration) plus filtration.

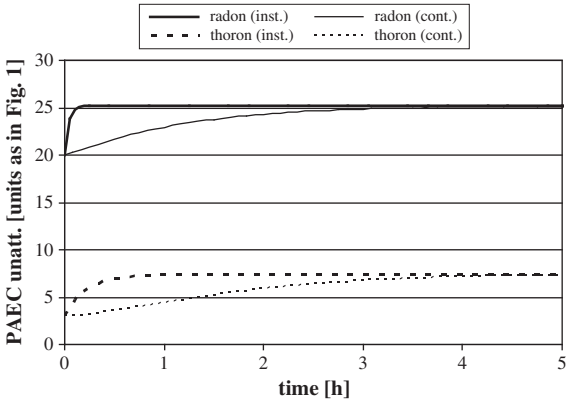

Fig. 2. Theoretically derived behavior of the concentrations of unattached radon and thoron decay products during filtration at a rate of 0.5 h^{-1} and at the same conditions as in Fig. 1. Two cases of the time dependence of the aerosol concentration are depicted: its new value is adopted instantaneously at the beginning of filtration (inst.) and the new value is adopted by a continuous exponential decrease of the concentration (cont.).

3.2. Measurement results

3.2.1. Filtration with an HEPA filter

Fig. 3 compares the temporal behavior of attached radon (left) and thoron decay products (right) during filtration with the HEPA filter at different filtration rates. The filtration of the indoor air removed both radon and thoron decay products. However, the filtration efficiencies for the two decay chains varied strongly. For thoron decay products, the filtration efficiency was quite high in the terms of reduction of the *PAEC* (potential alpha energy concentration). It declined dramatically to only about 3% with a filtration rate of 0.8 h^{-1}; filtration at a rate of 0.5 h^{-1} reduced the *PAEC* to about 12% (theoretical value: 20%). For attached radon decay products, the filtration efficiency was much smaller for the lower filtration rates of 0.2 and 0.3 h^{-1} while concentrations of about 35% (theoretical value: 30%) to less than 10% where reached with filtration rates of 0.5 h^{-1} and larger.

The first undershoots of the displayed radon concentration within the first 20 or 30 h must be attributed to a measurement artifact: at those times small radon decay product concentrations were measured in the presence of still high thoron decay product concentrations, which nuclides could not be spectrometrically separated correctly. In fact, a reasonably monotonous decrease to the new equilibrium concentration is sensible. Also the decrease rate of attached thoron decay products is much smaller than expected; this must be ascribed to the lacking ability of the working level monitors to resolve small changes of the airborne decay product concentrations as described above.

Unattached radon and thoron decay products displayed temporal behaviors which differed from each other and from attached decay products during the filtration (Fig. 4). The concentration of unattached radon decay products remained approximately constant and at a filtration rate of 0.5 h^{-1} it increased slightly to about 120% (theoretical value: 130%) although the aerosol concentration decreased from about 2000 cm^{-3} to about 600 cm^{-3} at the same time (Fig. 5). In contrast, the concentration of unattached thoron decay products increased strongly to about 400% at the same filtration rate (theoretical value: 250%).

Thus, the theoretically derived general behavior could be confirmed by the measurement results. However, with some of the input parameters of the theoretical model bearing large uncertainties (such as the deposition velocity) not all of the predicted ratios of concentrations before and during filtration could be retrieved.

Recently, Joshi et al. (2010) used unipolar ionizers as a different approach to mitigate thoron decay products by increased deposition to surfaces and found similar results: Whereas the concentration of total thoron decay products was decreased to about 20 to 25% of the original value, the unattached fraction increased from e.g. 2 to 6.5% at the same time due to simultaneous reduction of the aerosol concentration. This resulted in a significant mitigation of the inhalation dose by a factor of about 5. In contrast to mitigation by filtration the concentrations changed within a few minutes in two small volumes (1 and 16 m^3) and within 1 h in a larger volume, which might be caused by a larger sink rate.

All influencing parameters from Eq. 5 to Eq. 8 (such as air exchange rate and deposition rate) are also effective in real dwellings. For this reason the filtration results are valid also there. However, the filtration rate must be calculated from the volume of the respective room; e.g. the air flow rate through the HEPA filter which resulted in a filtration rate of 0.8 h^{-1} in the experimental room yields a filtration rate of only 0.4 h^{-1} in a room of the double volume. Additionally, the aerosol concentrations before and during filtration can be different; a larger decrease of the aerosol concentration will result in a stronger increase of the concentration of unattached decay products. In large dwellings with many rooms it might be necessary to perform filtration in several rooms (such as living room and sleeping room) and can be combined with air conditioning systems.

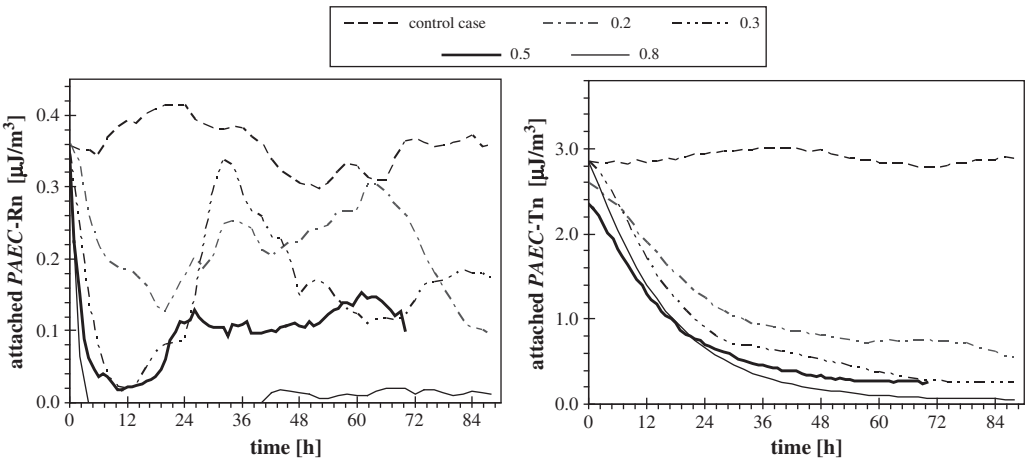

Fig. 3. The temporal behavior of attached radon (left) and thoron decay products (right) during filtration with an HEPA filter under different filtration rates (0.2, 0.3, 0.5, and 0.8 h^{-1}) in the experimental room. Measurement uncertainties are between 7% at the beginning and 20% during filtration for each two-hour measurement (single standard deviation).

3.2.2. Filtration with a surgical mask

The temporal behavior of attached and unattached radon and thoron decay products during filtration with a surgical mask and a household fan (air flow rate through the system 20 m^3/h, i.e. nominal filtration rate 3 h^{-1}) are shown in Figs. 6 and 7. Also with this low-cost device a significant decrease of the concentrations of attached decay products could be found. Attached thoron decay products reached a concentration of equilibrium of 30%, attached radon decay products of only 20% of the respective value without filtration. Also during this filtration, the concentration of unattached decay products increased: to about 130% for the radon decay products and to about 270% for the thoron decay products.

Although this filtration set-up does not comprise a closed loop, it is more effective than the set-up with the HEPA filter for long operation times. However, the concentration of attached decay products decreases significantly slower than with the HEPA filter as the filtration with the mask acts more locally in the proximity of the device at the beginning. This can be modeled with a filtration rate which increases within 60 h to an effective value of 0.8 h^{-1}.

In larger rooms a filtration with one mask and at the same air flow rate can yield an even longer time until filtration reaches its equilibrium in the whole room. Additionally the effective filtration rate can be smaller than in the experimental room due to a strong local effect of filtration. Then it might be reasonable to use several such devices distributed within the room.

3.3. Implications to the inhalation dose

The received dose following the inhalation of radon and thoron decay products is caused by two contributions: the inhalation of attached decay products and that of unattached decay products, where the airborne concentration of the latter is smaller but the dose coefficient is larger. Therefore a decrease of the concentration of the total (and thus also of the attached) decay products does not necessarily mean a decrease of the inhalation dose if, as observed, the concentration of unattached decay products increases at the same time as a consequence of a smaller aerosol concentration. Applying dose coefficients from the literature (Kendall and Smith, 2002; Li et al., 2008), the doses before and during filtration can be calculated and the influence of the filtration on the inhalation dose can be assessed. Results are shown in Table 2. For these values a contribution of the two nuclides of each decay chain according to the ratio of concentrations which was found in the theoretical calculation was assumed. A breathing rate of 0.78 m^3/h and a daily stay in that room of 10 h (40%) were used.

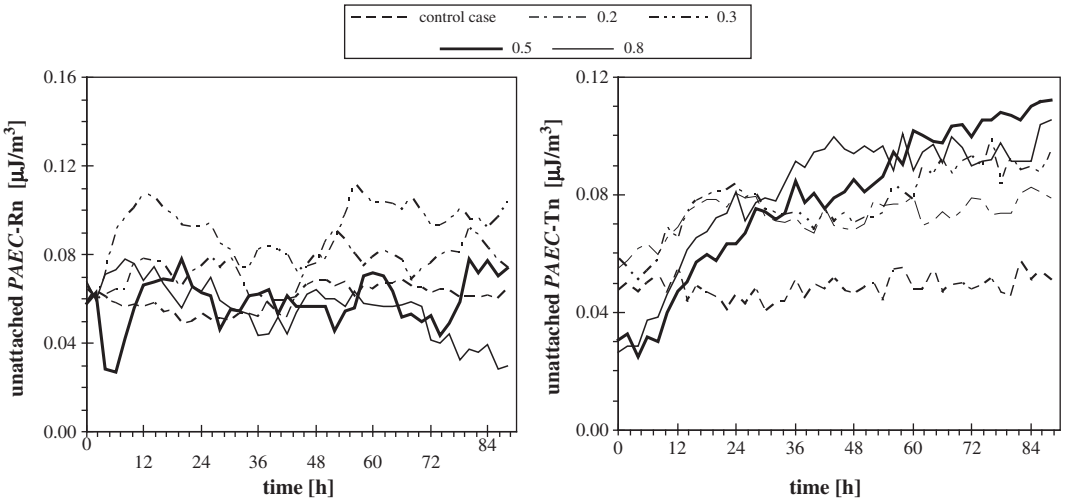

Fig. 4. The temporal behavior of unattached radon (left) and thoron decay products (right) during filtration with an HEPA filter under different filtration rates (0.2, 0.3, 0.5, and 0.8 h^{-1}) in the experimental room. Measurement uncertainties are about 15% for each two-hour measurement (single standard deviation).

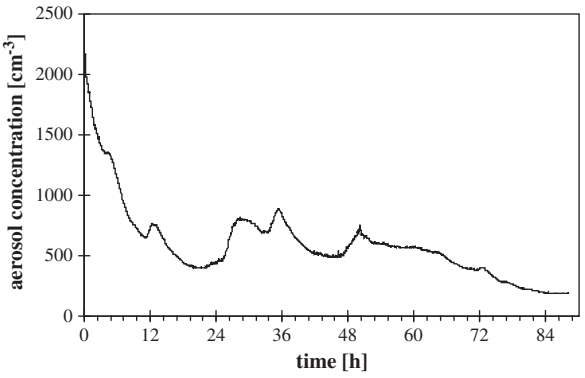

Fig. 5. Temporal behavior of the aerosol concentration in the experimental room during filtration with an HEPA filter at a rate of 0.5 h^{-1}.

Although the dose caused by the inhalation of unattached decay products is strongly increased, the overall inhalation dose from thoron decay products could be decreased significantly both with the HEPA filter and with the surgical mask. This is caused by the small concentration and contribution of unattached thoron decay products. For the radon decay chain, where unattached decay products play a more important role, the decrease of the inhalation dose is less pronounced. However, how much the dose rises from unattached decay products depends on the decrease of the aerosol concentration during filtration; if in other rooms the aerosol concentration decreased less, the dose from unattached decay products also changes

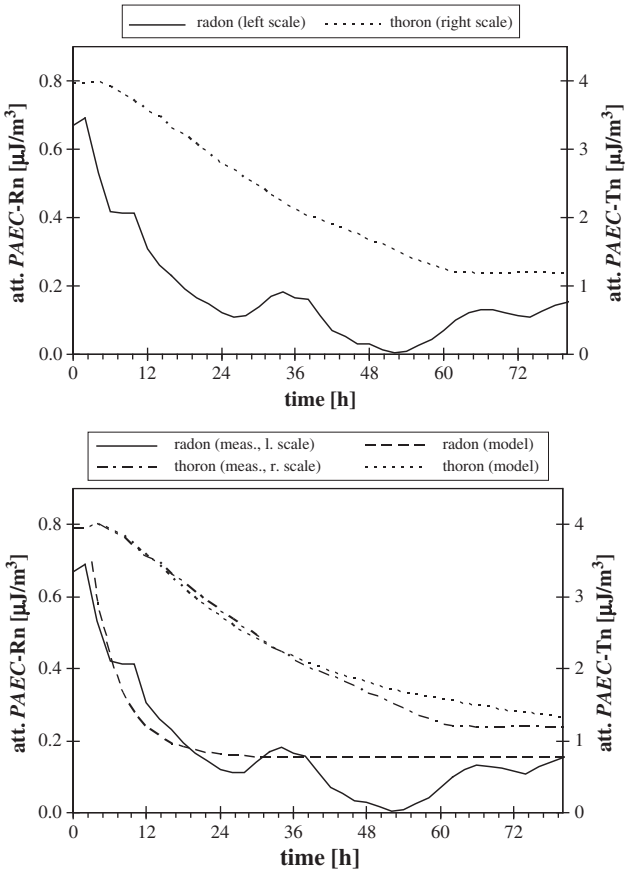

Fig. 6. The measured temporal behavior of attached radon and thoron decay products during filtration with a surgical mask in the experimental room. Measurement uncertainties are about 10% for each two-hour measurement (single standard deviation). Additionally, results from model calculation with an effective filtration rate of 0.8 h^{-1} are shown.

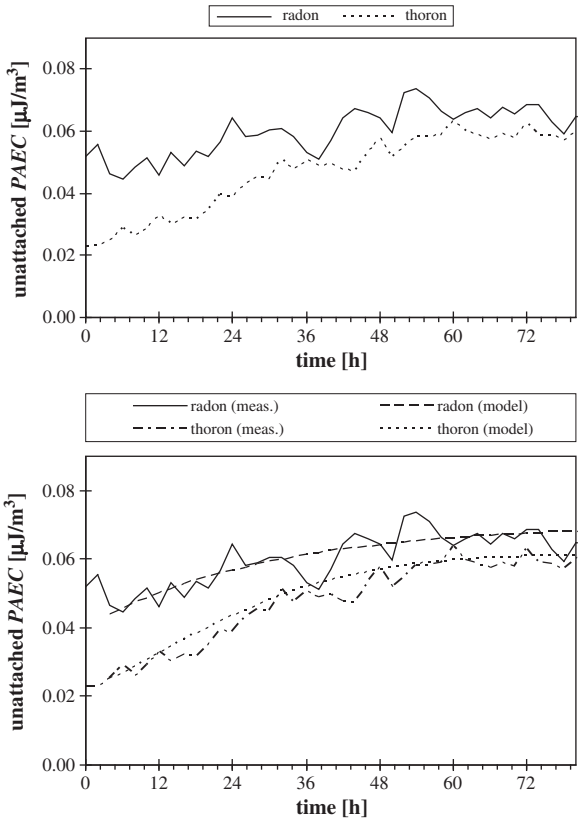

Fig. 7. The measured temporal behavior of unattached radon and thoron decay products during filtration with a surgical mask in the experimental room. Measurement uncertainties are about 15% for each two-hour measurement (single standard deviation). Additionally, results from model calculation with an effective filtration rate of 0.8 h^{-1} are shown.

less. Additionally, if the unattached fraction of radon decay products is small, the adverse affect of filtration on unattached decay products will play a smaller role for the inhalation dose; this leads to a more distinct decrease of the inhalation dose.

The relative temporal behavior of the inhalation dose rate was calculated from the solution of the differential equations with an assumed continuous change of the aerosol concentration; it is shown in Fig. 8. Both for radon and for thoron decay products, a decrease of the inhalation dose can be achieved only after several hours of filtration.

4. Conclusions

The results of active mitigation with different filtration rates show that filtration rates of 0.2 h^{-1} and larger are sufficient to substantially decrease the concentrations and the inhalation dose of thoron decay products — rates which can easily be obtained with common household air cleaning systems. Even with low cost devices as a fan with a surgical mask a significant mitigation of the thoron inhalation dose can be achieved. The slow decrease of the concentration of attached thoron decay products, however, makes it necessary to perform filtration also several hours before a room is entered or permanently. In large rooms, it might be necessary to operate several filtration devices distributed in the room simultaneously. If the aerosol concentration decreased strongly as a result of the filtration, the decreased concentration of attached decay products can be compensated by an increased concentration of unattached decay products. Thus, it is suggested to test whether the increasing contribution of the unattached decay products due to the low aerosol concentration can be reduced by adding aerosol particles to the indoor

Table 2
Influence of permanent filtration with an HEPA filter at 0.5 h^{-1} and with a surgical mask at 3 h^{-1} in the experimental room on the annual dose following the inhalation of radon decay products (Rn DP) and thoron decay products (Tn DP).

	Filtration					
	With HEPA filter			With surgical mask		
	Dose without filtration [mSv]	Dose with filtration [mSv]	Relative change	Dose without filtration [mSv]	Dose with filtration [mSv]	Relative change
Rn DP unattached	7.2	8.5	+17%	6.0	7.9	+30%
Rn DP attached	7.8	2.6	−70%	13.3	2.6	−80%
Rn DP total	15.0	11.1	−26%	20.5	10.5	−45%
Tn DP unattached	0.83	3.3	+300%	0.61	1.7	+180%
Tn DP attached	9.9	1.2	−90%	15.9	4.6	−70%
Tn DP total	10.7	4.5	−60%	16.5	6.3	−60%

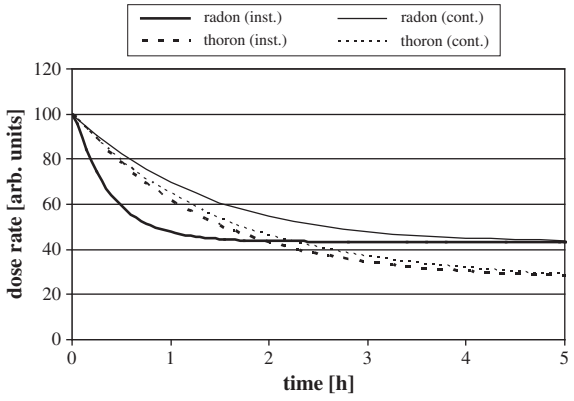

Fig. 8. The theoretically calculated temporal behavior of the inhalation dose rate from radon and thoron decay products at a filtration rate of 0.5 h^{-1}.

atmosphere. The small effect of filtration on the inhalation dose from radon decay products could be confirmed.

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