

RADON IN THE EXHALED AIR OF PATIENTS IN RADON THERAPY

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In the Gastein valley, numerous facilities use radon for the treatment of various diseases either by exposure to radon in air or in radon rich thermal water. In this study, six test persons were exposed to radon thermal water in a bathtub and the time-dependent radon activity concentration in the exhaled air was recorded. At temperatures between 38°C and 40°C, the radon activity concentration in the water was about 900 kBq/m³ in a total volume of 600 l, where the patients were exposed for 20 min, while continuously sampling the exhaled air during the bathing and 20 min thereafter. After entering the bath, the exhaled radon activity concentration rapidly increased, reaching some kind of saturation after 20 min exposure. The radon activity concentration in the exhaled air was about 8000 Bq/m³ at the maximum, with higher concentrations for male test persons. The total radon transfer from water to the exhaled air was between 480 and 1000 Bq, which is equivalent to 0.08% and 0.2% of the radon in the water.

INTRODUCTION

Radon treatment in the Gastein valley has a long tradition and can be traced back to the medieval ages. The treatment has been applied for chronic pain and functional disorders in case of diseases affecting the locomotive apparatus, regeneration, circulation and immunologic skin balance disorders and functional disorders of the respiratory tract⁽¹⁾. According to several studies, the treatments have proven to be successful without having a complete understanding of the underlying cellular and molecular mechanisms^(2, 3) and somehow, despite all odds, of the harmfulness of radon. In the treatment procedures radon is applied either (1) as thermal bath in radon rich water or (2) exposure to radon rich atmosphere in the ‘vapour bath’ in a special exposure chamber, or in the Thermal Gallery, a former gold exploration mine.

The patients in the thermal bathtubs are exposed to radon activity concentrations of the order of 1 MBq/m³ in water for a period of 20 min at temperatures between 37°C and 40°C. The exposure conditions in the vapour bath are more varying: the radon activity concentration lies between 30 and 300 kBq/m³, at 37°C temperature of the radon enriched vapour, which is supplied by degassing of thermal water. In the Thermal Gallery, the concentration range is similar to the vapour bath, on average the radon activity concentration is 45 kBq/m³ in a very humid atmosphere, with 95–99% RH at temperatures between 36°C and 40°C.

Therapeutic effects have been attributed to radon doses in specific organs of the human body depending on the different exposure pathways. These are radon and radon progeny uptake in the lungs in the Thermal Gallery and the vapour bath. In the radon water bath uptake through the skin and subsequent distribution in the body dominates above lung uptake. However, therapeutic effects are widely attributed to radon uptake through the lung. Recently, Tempfer *et al.*⁽⁴⁾ proposed an immune response by irradiation of the skin after radon progeny deposition as an alternative to lung deposition.

Models for lung dosimetry⁽⁵⁾, radon progeny deposition on the skin⁽⁴⁾ and organ dose models for radon incorporation⁽⁶⁾ have been published⁽⁷⁾. Recently, Hofmann and Winkler⁽⁸⁾ extended the radon incorporation model of Petermann and Perkins⁽⁹⁾ to include water–skin–blood transfer to simulate the radon activity concentration in the exhaled breath and in organs (RADMOD). The model was developed further and will be applied to the experimental data of the present study⁽¹⁰⁾. The radon transfer water–skin–blood can be derived by time resolved radon activity concentration measurements in the exhaled air of patients, if the contribution of inhalation can be kept negligible by inhaling radon-free air. These experimental measurements were started in a radon treatment facility in Bad Hofgastein with six test persons of different age and sex, with the objective to produce a solid data base for the extension of the RADMOD model.

METHODS

For the measurement of the time-dependent radon activity concentration in the exhaled air, it would be most desirable to measure radon directly in the exhaled air to obtain the time behaviour. However, this is wishful thinking as there are no commercially available instruments to fulfil these requirements at the volume flow of breathing. So the authors decided to alternatively sample the air stream in predefined intervals and perform the radon measurements in the laboratory with Lucas cells.

Selection of site and test persons

The experiments were carried out in the 'Thermalkurhaus' in Bad Hofgastein, a facility with a long standing tradition in supplying radon therapy in bathtubs for the treatment of patients of the state health care system and private patients. The test persons for the experiments were four female and two male persons in the age range between 26 and 40 y in order to cover age influence and gender differences. Two female test persons were measured twice to investigate any individual temporal variations. The personal details of the six test persons are listed in Table 1. The persons were taking a radon bath for 20 min in the Best'sche Wanne' (Figure 1), a bathtub of 600 liter volume, at temperatures between 38°C and 40°C.

Gas bags for exhaled air sampling

For sampling the exhaled air, the authors had to develop suitable gas bags with a small volume to store the exhaled air for later measurements. Commercially available gas bags for laboratory use are commonly too large or not suitable to be appropriately used to sample the tidal volume of a breathing person, which is 750 ml for a male person at sitting-awake conditions⁽¹¹⁾. Small gas bags were prepared to sample 1.5 l on the basis of commercially available helium fun balloons. The balloons, with a volume of 10 l, are made of an aluminium coated

polyethylene foil. The size of the balloons was reduced by sealing the edgings with an ordinary kitchen vacuum sealer. The simple procedure with this type of material turned out to be sufficiently radon-tight to store the exhaled air samples for two weeks, which is needed to complete the measurements for a whole experiment. In a number of trials, the radon tightness was tested by subsequently extracting fillings for a Lucas cell without detecting any radon loss over a period of two weeks.

Application/construction of breathing mask

For reducing the contribution of inhaled radon to radon uptake to a minimum, the authors decided to provide ambient air for inhalation. This was managed with a 10 m long hose, connected to the outdoor environment through an open window. In order to establish a low flow resistance and to avoid additional efforts for breathing for the patients, a diameter of 5 cm was selected for the hose. The hose was connected to a mask for the test persons. The mask was equipped with a shuttle valve to switch between breathing in ambient air and breathing out into the



Figure 1. Test person in the Best'sche Wanne with a mask for breathing almost radon-free outdoor air and sampling the exhaled air.

Table 1. Individual body characteristics and respiratory parameters of the test persons (TP): tidal volume (V_T), body surface area (SA), breathing frequency (BF), estimated radon transfer (RT) and RT normalised.

TP	Sex	Age (yr)	Weight (kg)	V_T (l)	SA (m ²)	BF (min ⁻¹)	RT (Bq)	RT norm. (10 ⁶ m/kg)
1	F	36	58	0.56	1.65	15.3	530 680	0.077 0.080
2	F	26	52	0.52	1.52	20.5	520	0.076
3	F	28	57	0.52	1.59	13.9	430	0.049
4	F	32	62	0.52	1.68	15.0	540	0.062
5	M	40	90	0.72	2.14	14.0	1000	0.070
6	M	28	83	0.70	2.08	11.1	890	0.064

bathing room or into the gas bags for sampling. A sketch of the breathing mask is shown in Figure 2.

The mask was designed to prevent bypass flow along the edging of the mask with sealing lips attached to facial skin tightly. For technical reasons, the arrangement of the shuttle valve, which actually is a combination of two valves, requires a dead space of 110 cm³ and an additional volume of 40 cm³ in the exhalation branch. The dead space causes a contribution of inhaled air to the sampled exhaled air and has to be considered when calculating the activity of the exhaled air:

V_D	Dead space, 110 ml
V_R	Remaining volume of the preceding exhalation (breath), 40 ml
$C_{(n)}$	Radon activity concentration of the n th exhalation cycle
V_T	Tidal volume
C_{Air}	Radon activity concentration in the outdoor air
C_B	Radon activity concentration sampled in the gas bag

The radon activity concentration sampled in the gas bag is then computed as follows:

$$C_B = [C_{(n)} (V_T - V_D - V_R) + V_D C_{Air} + V_R C_{(n-1)}] / V_T$$

$C_{(n)}$ can be calculated easily if the term $V_R C_{Air}$ was ignore and set $C_{(n-1)} = C_{(n)}$. Both simplifications are justified as they do not have any significant

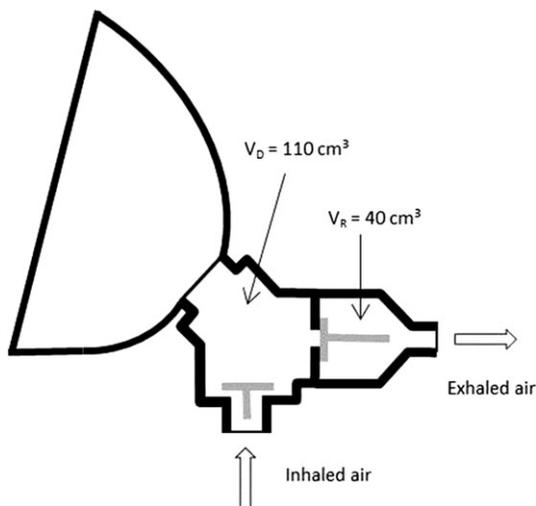


Figure 2. Sketch of breathing mask and relevant volumes for activity correction. Shuttle valves are grey shaded.

influence on the outcome: C_{Air} , the concentration of the outdoor air, is in the range of 10 Bq/m³ and two orders of magnitude lower than the concentration of the exhaled air at maximum level, but still much lower than $C_{(n)}$ at the onset of the exhalation. The sampling rate for the exhaled air is normally set at 4 min interval length. Considering an average breathing rate of 15 breathing cycles per minute (compare Table 1), a 4 min interval length for sampling is equivalent to sample one out of 60 breathing cycles. In addition, a correction for the ambient air pressure in the laboratory (pL at 450 m AMSL) and the site of the thermal bath in Bad Hofgastein (pBH at 859 m AMSL) has to be applied. Thus, the concentration in the exhaled air at the n th cycle is:

$$C_{(n)} = C_B V_T / (V_T - V_D) * (pBH/pL).$$

Determination of tidal volume V_T

Spirometry measurement

Spirometry (frequency and tidal volume V_T) was examined using the human respiratory kit combined with a PowerLab 4/25T (ADInstruments). Laminar airflow produces a pressure differential on a fine gauze that is linearly proportional to the velocity. Spirometry data was recorded using Labchart 7. The tidal volume and respiratory rate were calculated by the software. Due to technical feasibility, only the inhalation could be recorded. Recording the exhalation would have enlarged the dead space drastically.

RESULTS AND DISCUSSION

The radon diffusion through the skin is proportional to the radon activity concentration in the bathing water. However, the radon activity concentration in the water is not absolutely constant throughout the bathing phase as the filling procedure necessarily swirls the water and during the bathing phase radon can emanate from the water surface, thus reducing the concentration in the remaining water. Another loss of radon takes place through diffusion into the patient's body and exhalation by ongoing breathing cycles. The total radon decrease is between 0.7% and 7.7% of the initial concentration (Figure 3). By far the major contribution of the radon loss comes from emanation of the water surface. The estimated radon transfer, i.e. radon loss by diffusion into the patient and subsequent exhalation is in the range between 430 Bq and 1000 Bq for a bathing phase of 20 min, which is between 0.08% and 0.2% of the total radon in the bath water (Table 1).

In one additional experiment with 30 min bathing phase with a female test person, that it made to determine the radon saturation in the exhalation phase, the

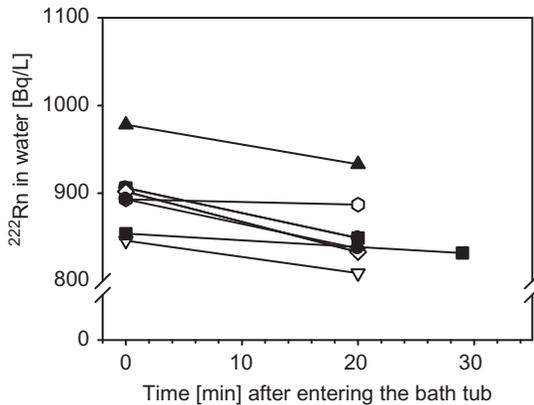


Figure 3. ^{222}Rn concentration in water at the beginning and at the end of the bath, after 20 or 30 min.

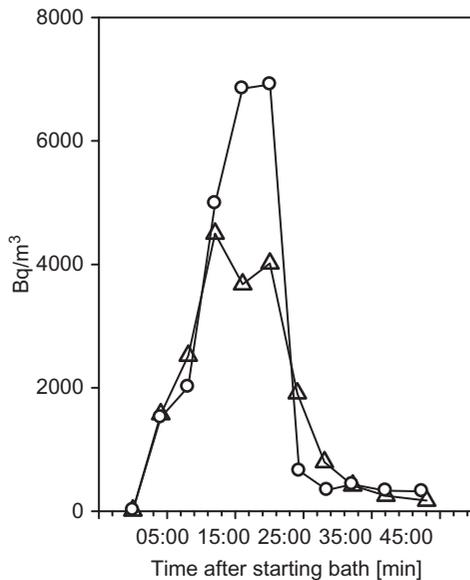


Figure 4. ^{222}Rn concentration in the exhaled air of a male (circles) and a female (triangles) test person exposed in water with 880 kBq/m^3 .

radon transfer was 1170 Bq . During the bath, the radon activity concentration in the exhaled air increased rapidly immediately after entering the bath.

In Figure 4, two examples for a female and a male test person are shown, which differ significantly in the concentration of the exhaled air, both of them normalised to the same radon activity in water. The data suggest that after a 20 min bathing phase some kind of plateau in the concentration of the exhaled air will be reached. There are also some hints that

the shape of the saturation curve may be sigmoidal with a point of inflection. This shape cannot be explained with the common models of coupled linear differential equations for the radon transfer. (Details are to be published in a publication in preparation on modelling the radon transfer in the radon bath.) The observed differences of the radon activity concentration in the exhaled air reflect the influence of the patient's skin surface area, which is crucial for diffusion, and the volume of the exhaled air, the product of tidal volume, breathing rate and time. The time-dependent radon activity concentration was used in the exhaled air to calculate the radon transfer by integrating over the exhaled volume. There are significant differences between female and male test persons, as listed in Table 1.

To eliminate the influence of a test person's mass and surface area, the results were normalised to the radon activity concentration in water, in MBq/m^3 , to the weight and surface area of the test persons, yielding the somewhat peculiar unit of m/kg . According to that normalisation, the differences vanish and the results of male and female persons overlap (Table 1).

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