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Investigation of the exposure to radon and progeny in the thermal spas of Loutraki (Attica-Greece): Results from measurements and modelling

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Radon and progeny (^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) in thermal spas are well known radioactive pollutants identified for additional radiation burden of patients due to the activity concentration peaks which appear during bath treatment or due to drinking of waters of high radon content. This burden affects additionally the working personnel of the spas.
The present paper has focused on the thermal spas of Loutraki (Attica-Greece). The aim was the investigation of the health impact for patients and working personnel due to radon and progeny. Attention has been paid to radon and progeny transient concentration peaks (for bath treatment) and to radon of thermal waters (both for bath treatment and drinking therapy). Designed experiments have been carried out, which included radon and progeny activity concentration measurements in thermal waters and ambient air.
Additionally, published models for description of radon and progeny transient concentration peaks were employed. The models were based on physicochemical processes involved and employed non linear first order derivative mass balance differential equations which were solved numerically with the aid of specially developed computer codes. The collected measurements were analysed incorporating these models. Results were checked via non linear statistical tests. Predictions and measurements were found in close agreement. Non linear parameters were estimated.
The models were employed for dosimetric estimations of patients and working personnel. The effective doses of patients receiving bath treatment were found low but not negligible. The corresponding doses to patients receiving potable treatment were found high but below the proposed international limits. It was found that the working personnel are exposed to considerable effective doses, however well below the acceptable limits for workers. It was concluded that treatment and working in the Loutraki spas leads to intense variations of radon and progeny and consequently additional health impact both to patients and working personnel.

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1. Introduction

Radon (^{222}Rn) is a naturally occurring radioactive gas formed by the decay series of ^{238}U which disintegrates to a series of short-lived radioactive decay products (progeny) (^{218}Po, ^{214}Bi, ^{214}Pb and ^{214}Po). Radon and progeny are recognised as the most significant natural source of human radiation exposure (UNSCEAR, 2000) and the most important cause of lung cancer incidence except for smoking (US-EPA, 2003; WHO, 2006).

Considerable high concentrations of radon and progeny have been observed in thermal spas (Steinhäusler, 1988; Lettner et al., 1996; Szerbin, 1996; Trabidou et al., 1996; Datye et al., 1997; Vogiannis et al., 2004a,b,c; Radolic et al., 2005; Song et al., 2005; Manic et al., 2006; Bonotto and Santos, 2007; Somlai et al., 2007; Gnoni et al., 2008) causing significant additional radiation burden to patients and working personnel. The EU has identified this fact in the directive 96/29/EURATOM, proposing spa therapy as a professional activity of enhanced natural radiation exposure (CEC, 1996).

In Greece, thermal spa therapy is well accepted by the Greek National Health System. Therefore, it is frequently recommended by medical doctors. This fact leads many individuals to visit such centres for treatment through baths (bath treatment) or drinking of thermal water. On account of the related health risk and the recent tendency of introducing spa centres as recreation sites or as health resorts, the reporting team investigates the radiation exposure of patients and working personnel due to radon and progeny (Geranios et al., 2004; Vogiannis et al., 2004a,b,c; Vogiannis 2005; Nikolopoulos and Vogiannis, 2007; Vogiannis and Nikolopoulos, 2008). Recently (2007), the generation of radon progeny transient concentration peaks in thermal spas in Greece has been modelled (Nikolopoulos and

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Vogiannis, 2007). Modelling was achieved through simulation of the involved physical procedures through a set of first order time-varying differential equations (dynamical approach) and a set of parameters of physical interest (semi-empirical modelling). In addition, the generation of the concentration peaks of radon and the corresponding temporal variations, were modelled on the basis of physicochemical processes involved, by employing non linear first order derivative mass balance differential equations and specially developed computer codes (Vogiannis and Nikolopoulos, 2008).

The present paper has been focused on radon and progeny of the thermal spas of Loutraki (Attica-Greece) (Fig. 1). The aim was the investigation of the radiation burden to patients and working personnel through measurements and modelling. Towards this, radon and progeny activity concentrations were determined and analysed incorporating the abovementioned models.

2. Materials and methods

2.1. Area of study

Loutraki (Fig. 1) is located northwest of Athens on the Gulf of Corinth coast (latitude 37.58° N and longitude 22.58° E). Loutraki is considered as the most ancient bathing resort of Greece. It is distinguished as a principal therapeutic spot. It is famous for its spas which are recommended for disorders of the urinary tract, gravel, stones in kidney, gallstones and gout.

The main spa centres of Loutraki are two; the building of the municipal thermal spas (BMTS) and the building of the spring (BS). The BMTS includes 25 treatment rooms (TRs) for bath treatment of patients and a large reception room (RR) which serves for management and administration. The TRs contain bathtubs of 8 m^{-3} equipped with taps providing spring (thermal) and non-spring water, places for dressing and sanitary purposes, windows for natural ventilation, a small mechanical system which may be utilised for forced ventilation and a door. Spring water is periodically pumped from its source by means of a mechanical drainage system located a few meters outside the BMTS. The pumped water may be used instantly, but for most of the cases, it is stored in a water tank until drained. The water in the tank may be used at the tank's temperature (cold water) or after heat supply (hot water); however the latter is not advisable. Under regular conditions, the spa personnel is responsible for bath filling, managing of the mechanical and natural ventilation system, bath emptying and cleaning and overall functioning of the TR. The BS, named after its position, is built around a physical spot from which spring water enters straight from two different sources named after their spring content; the Heavy Source (HS) and the Light Source (LS). Both sources are different from the one located outside the BMTS and are utilised for drinking therapy of patients. The working personnel reside in the building and are responsible for the services related to the drinking therapy, i.e., cleaning of glasses, filling of ewers, opening and closing of the centre.

The regular recommendations are 30 sequential days of bath treatment or 15 sequential days of drinking therapy. The advised bath treatment programme requires the stay of the patient into the bathtub for 30 min/day. However, according to the practice followed by the majority of the patients receiving a bath, the advised 30 min programme includes additional time for the filling of the bathtub. The advised drinking therapy programme entails the sequential consumption of three 350 mL glasses (total 1050 mL) of spring water.

2.2. Methods and measurement instrumentation

Radon and progeny measurements were collected during spring–summer (working period) of 2007 from the BMTS and the BS. Designed experiments were carried out in a manner that would allow dose estimations, as well as, modelling of radon and progeny peaks according to the models (Nikolopoulos and Vogiannis, 2007; Vogiannis and Nikolopoulos, 2008). The experience gained from previous relevant works (Geranios et al., 2004; Vogiannis et al., 2004a,b,c; Vogiannis 2005) was taken into consideration. The measurements involved the determination of the radon content of spring waters, the collection of transient radon and progeny peak concentrations in TRs

Fig. 1. Map of Loutraki (Attica-Greece).

and the baseline radon and progeny concentrations in TRs and the RRs of both spas. The models were applied to collected data, to estimate parameters of interest. Doses of patients and working personnel were estimated through measurements and modelling.

To determine radon in water, 14 samples were collected from all possible sites, i.e., taps and the storage tank of the BMTS, the HS and the LS. Further samples were collected to determine the radon concentration of the entering water (A_{0w}) and the water of the bathtub at various time moments (A_w) in TRs (please see symbols in Table 1). This was achieved by an independent experiment. At first, the bathtubs of two neighbouring TRs were emptied and cleaned. The TRs were ventilated by opening simultaneously the windows and the door and by switching on the mechanical ventilation system for 20 min. This time interval was estimated to be large enough for the proper diminishing (<10% of the maximum value) of any radon and progeny peaks and the restoration of the baseline values in the TR. Thereafter, the bathtubs were simultaneously filled with spring water up to a fixed level. To determine A_{0w}, 5 samples were received immediately after the end of filling. To determine A_w, samples were received at scattered time moments after filling. All samples were taken at approximately 5–10 cm deep under the water surface, according to similar methodology followed in the thermal spas of Lesvos Island (Vogiannis, 2005). Sampling was done according to previous experience (Louizi et al., 2003) by proper radon proof storage vessels which were completely filled and closed under water to avoid formation of air bubbles. The sampled water quantity was refilled very slowly in the bath not allowing generation of air bubbles. Refilling was done by means of an identical storage vessel which contained spring water corresponding to the same time moment as the sampled one. This was received under identical methodology from the bathtub of the neighbouring TR. Measurements of radon in water were performed in-situ for the maximum allowed number of samples to achieve minimisation of radon decay. The remaining samples were measured later in the laboratory at the minimum achievable time interval to avoid any radon loses due to decay.

Table 1
Nomenclature.

Symbol	Units	Meaning
t	h	Time
λ_0	h^{-1}	Radon decay constant (0.00755)
λ_i	h^{-1}	Decay constants ($\lambda_1=13.37$, $\lambda_2=1.552$, $\lambda_3=2.111$)
λ_V	h^{-1}	Air exchange (ventilation) rate
$\lambda_{a,i}$	h^{-1}	Attachment rate constant of progeny in a TR during bath filling and treatment
$\lambda_{d,i}^{a}$	h^{-1}	Deposition rate constant of attached progeny in a TR during bath filling and treatment
$\lambda_{d,i}^{u}$	h^{-1}	Deposition rate constant of unattached progeny in a TR during bath filling and treatment
A_0	$Bq\cdot m^3$	Activity concentration of ^{222}Rn in a TR during bath filling and treatment
A_i^u	$Bq\cdot m^3$	Activity concentration of unattached progeny in a TR during bath filling and treatment
A_i^a	$Bq\cdot m^3$	Activity concentration of attached progeny in a TR during bath filling and treatment
A_i^s	$Bq\cdot m^3$	Surface (volume equivalent) activity concentration of deposited progeny in a TR during bath filling and treatment
$\bar{A}_e$	$Bq\cdot m^3$	Average activity concentration of ^{222}Rn in an empty TR
A_{0w}	$Bq\cdot m^3$	Activity concentration of radon in inflowing spring water
A_w	$Bq\cdot m^3$	Activity concentration of radon in spring water
a_{fc}	m^{-1}	Specific total interfacial contact area of "free and calm" surface
a_{eq}	m^{-1}	Specific total interfacial contact area of equivalent surface
K_L	$m\cdot h^{-1}$	Overall mass transfer coefficient
k	dimensionless	Ostwald coefficient
p_1	dimensionless	Recoil fraction of ^{218}Po

Index i equals 1,2,3 for ^{218}Po, ^{214}Pb and ^{214}Bi respectively.

To collect transient concentration peak data, radon and progeny activity concentrations were monitored in 7 TRs of the BMTS by means of 7 independent experiments of one week duration. Each experiment started and ended at 8:00 (opening time). Every day at 7:30 (8:00 opening time) and at 15:30 (16:00 closing time) the TR under investigation was ventilated for 20 min for the baseline values to be restored, as already described. Thereafter, the bathtub was emptied and cleaned, the windows and the door were closed and the mechanical ventilation system was switched off. The bathtub was filled with spring water at the storage tank's temperature, as only allowed to. This procedure lasted 10 min. In the time interval between two sequential procedures of bathtub's emptying and filling, the water in the bathtub and the TR was left unperturbed.

To collect baseline values, radon and progeny were monitored in the RRs of both spas and in 5 arbitrarily selected TRs. In the TRs the bathtubs were emptied, the windows and the door were closed and the mechanical ventilation system was switched off. Monitoring measurements in the RRs were done without interfering in the operation procedure. Since, the spa personnel are working for 8 h/day, the measurements in the RRs lasted 8 h/day and were collected during work. To estimate averages and ranges, the 8-h measurements were repeated 10 times.

Indoor radon activity concentrations (A_0) were measured using Alpha Guard PQ2000 Pro (AG) in 10-min measuring cycles (Genitron Instruments, 1997; Genitron Instruments, 1998). Indoor radon and progeny concentrations (A_0 and A_i^x) were measured by EQF3020 (EQF) in 2-h cycles (Sarad Instruments, 1998). The concentrations were monitored for 1 day similarly to previous methodology (Vogiannis et al., 2004a,b,c). Special care was taken to synchronise both instruments regarding the detection of radon peaks. This was achieved by controlling the simultaneous beginning of measurements of both instruments. Additionally, indoor activity concentrations of empty TRs (A_e) were monitored for 5 days to estimate averages. The collected data were considered representative for the calculation of the average time-series variations of the corresponding activity concentrations ($\bar{A}_e$). Measurements of radon in water were carried out by AG with a special unit (Aqua Kit, Genitron Ltd) according to standard methodology (Genitron Instruments, 1997; Louizi et al., 2003). Additionally, humidity was recorded by both instruments via special sensors.

2.2.1. Symbolisation, measured parameters, model application

The transient variations of radon activity concentration during treatment through bathing can be semi-empirically modelled (Vogiannis and Nikolopoulos, 2008) through Eq. (1.1):

$$\frac{dA_0}{dt} = \left[(\lambda_V + \lambda_0)\cdot \bar{A}_e\right] - \left[(\lambda_V + \lambda_0) + k\cdot K_L(a_{eq} + a_{fc})\right]\cdot A_0 + K_L(a_{eq}\cdot A_{0w} + a_{fc}\cdot A_w) \tag{1.1}$$

Symbols and units of Eq. (1.1) are given in Table 1. As aforementioned and for the semi-empirical approach, the parameters A_0, $\bar{A}_e$, A_{0w} and a_{fc} (please see Table 3) were measured. K_L was taken equal to $4.2\cdot10^{-4}$ $m\cdot h^{-1}$ (Corbett et al., 1997; Calugaru and Crolet, 2002), k to 0.276 and λ_V to 0.5 h^{-1}. A_w was estimated mathematically by the power model

$$A_w = A_{0w}t^{-d} \tag{1.2}$$

from the collected measurements and similarly to modelling in the spas of Lesvos Island (Greece) (Vogiannis, 2005; Vogiannis and Nikolopoulos, 2008). From the whole model, a_{eq} was estimated.

The variations of progeny activity concentrations can be modelled through system Eqs. (2.1)–(2.9) (Nikolopoulos and Vogiannis, 2007):

$$\frac{d}{dt}(A_1^{u}) = \lambda_1 A_0 - (\lambda_1 + \lambda_V + \lambda_{a1,} + \lambda_{d,1}^{u})\cdot A_1^{u} \tag{2.1}$$

$$\frac{d}{dt}(A_1^{a}) = \lambda_{a,1} A_1^{u} - (\lambda_1 + \lambda_V + \lambda_{a,1} + \lambda_{d,1}^{a})\cdot A_1^{a} \tag{2.2}$$

$$\frac{d}{dt}(A_1^{s}) = \lambda_{d,1}^{u} A_1^{u} + \lambda_{d,1}^{a} A_1^{a} + \lambda_1 A_1^{s} \tag{2.3}$$

$$\frac{d}{dt}(A_2^{u}) = \lambda_2 A_1^{u} + p_1 \lambda_2 A_1^{a} - (\lambda_2 + \lambda_V + \lambda_{a,2} + \lambda_{d,2}^{u})\cdot A_2^{u} \tag{2.4}$$

$$\frac{d}{dt}(A_2^{a}) = \lambda_{a,2} A_2^{u} + (1-p_1)\lambda_2 A_1^{a} - (\lambda_2 + \lambda_V + \lambda_{a,2} + \lambda_{d,2}^{a})\cdot A_2^{a} \tag{2.5}$$

$$\frac{d}{dt}(A_2^{s}) = \lambda_2 A_1^{s} + \lambda_{d,2}^{u} A_2^{u} + \lambda_{d,2}^{a} A_2^{a} - \lambda_2 A_2^{s} \tag{2.6}$$

$$\frac{d}{dt}(A_3^{u}) = \lambda_3 A_2^{u} - (\lambda_3 + \lambda_V + \lambda_{a,3} + \lambda_{d,3}^{u})\cdot A_3^{u} \tag{2.7}$$

$$\frac{d}{dt}(A_3^{a}) = \lambda_3 A_2^{a} + \lambda_{a,3} A_3^{u} - (\lambda_3 + \lambda_V + \lambda_{d,3}^{a})\cdot A_3^{a} \tag{2.8}$$

$$\frac{d}{dt}(A_3^{s}) = \lambda_3 A_2^{s} + \lambda_{d,3}^{u} A_3^{u} + \lambda_{d,3}^{a} A_3^{a} - \lambda_3 A_3^{s} \tag{2.9}$$

Symbols and units of system Eqs. (2.1)–(2.9) are also given in Table 1.

The application of model Eqs. (2.1)–(2.9) was also semi-empirical. The parameters λ_0, λ_i and p_1 were considered of fixed values (please see Table 1), λ_V was taken equal to 0.5 h^{-1}, whereas the time-series A_i^{u}, A_i^{a} were directly measured. From the model $\lambda_{a,i}$, $\lambda_{d,i}^{a}$, $\lambda_{d,i}^{u}$ were estimated.

Modelling through Eqs. (1.1)–(1.2) and (2.1)–(2.9) was performed through numerical solving of 3000 iterations according to Levenberg–Marquardt fit methods, described in the related publications. In this consensus, the time-series values of the parameters A_0, A_i^{u} and A_i^{a} were used for the generation of the corresponding time-series functions (fitted time-series functions) which were utilised instead of the measured time-series data. The fitted time-series A_0 functions generated by the recordings of AG were employed in Eqs. (1.1)–(1.2) and (2.1)–(2.9) due to the quicker and more precise response of AG, compared to EQF, in measuring pure radon. (Vogiannis and Nikolopoulos, 2008). However, for comparison purposes, the radon recordings of EQF were also used. Efficiency of modelling was also checked under similar methodology by means of five statistical tests:

(i) Chi-square test: fit acceptance criterion: $\chi^2 < \chi^2_{\mathrm{critical}}$, $\chi^2_{\mathrm{critical}} = 3183$ ($N = 3000$ iterations) at error probability $^{**}p < 1\%$ (Mendenhall and Sincich, 1994).

(ii) Reduced chi-square test: fit acceptance criterion: $\chi^2_\nu \cong 1$ at probability $p = 50\%$ (or at least $\chi^2_\nu < 1$ at $p > 50\%$) (Bevington, 1969).

(iii) Correlation test: fit acceptance criterion: adjusted or Pearson $r^2 > 0.9$.

(iv) F test: fit acceptance criterion: $\frac{1}{F_{\mathrm{critical}}} < F < F_{\mathrm{critical}}$, $\frac{1}{F_{\mathrm{critical}}} = 0.906$ and $F_{\mathrm{critical}} = 1.10$ at error probability $^{**}p < 1\%$ (Bevington, 1969; Mendenhall and Sincich, 1994).

(v) Wilcoxon matched pairs test: fit acceptance criterion: $Z < Z_{\mathrm{critical}}$, $Z_{\mathrm{critical}} = 2.58$ at error probability $^{**}p = 1\%$.

2.2.2. Exposure and dosimetric calculations

2.2.2.1. BMTS. Dose estimations were based on the modelled time-series functions A_i^{u} and A_i^{a}. From these, the time-series values of the Potential Alpha Energy Concentration (PAEC) (MeV·L^{-1}), the equilibrium factor (F) and the unattached fraction in terms of PAEC (f_p) were calculated according to standard definitions (Nazaroff and Nero, 1988):

$$PAEC = \sum_{x=a,u} (3.69\cdot A_1^{x} + 17.83\cdot A_2^{x} + 13.12\cdot A_3^{x}) \tag{3.1}$$

$$F = \frac{0.106\cdot(A_1^{a} + A_1^{u}) + 0.513\cdot(A_2^{a} + A_2^{u}) + 0.381\cdot(A_3^{a} + A_3^{u})}{A_0} \tag{3.2}$$

$$f_p = \frac{3.69\cdot A_1^{u} + 17.83\cdot A_2^{u} + 13.12\cdot A_3^{u}}{\sum_{x=a,u}(3.69\cdot A_1^{x} + 17.83\cdot A_2^{x} + 13.12\cdot A_3^{x})} \tag{3.3}$$

In the above equations, $i = 1, 2, 3$, represent ^{218}Po, ^{214}Bi, ^{214}Pb respectively and a,u distinguish the contributions of the two states (attached, unattached) of radon progeny.

From PAEC values of Eq. (3.1), time-series Potential Alpha Energy Exposure (PAEE) (mWLM) values were calculated according to

$$PAEE(t) = CF_1 \cdot \int_0^t PAEC\cdot dt \tag{3.4}$$

where t(h) is the time moment and $CF_1 = 4.446\cdot 10^{-8}$(WLM/MeV·$L^{-1}$·h) is an exposure conversion factor.

From PAEE values of Eq. (3.4), time-series values of the Cumulative Effective Dose (CED) (μSv) were calculated according to

$$CED(t) = PAEE(t)\cdot DCF_1(t) \tag{3.5}$$

where t (h) is the time moment and $DCF_1(t) = 6.1 + 42\cdot f_p \times 10^6$ (nSv/WLM) (Porstendörfer, 2001) is a time-varying conversion factor.

To calculate the additional annual Effective Dose ($ED_{p,BMTS}$(μSv·y^{-1})) of a patient receiving a full bath treatment programme (index p stands for patient and index BMTS, for bathing in the BMTS, as already mentioned, it was considered that each patient receives 30 treatments annually of 30 min duration. This time was, however, extended to 40 min accounting for the aforementioned normal practice to lengthen the bath treatment with the 10-min time needed for bath filling. Calculation was done according to Eq. (3.6)

$$ED_{p,BMTS} = CED\left(t = 0 \rightarrow t = \frac{40\ \mathrm{min}}{60\ \mathrm{min}\cdot h^{-1}}\right)\cdot 30y^{-1} \tag{3.6}$$

To calculate the additional annual Effective Dose of a member of the spa personnel (worker) ($ED_{w,BMTS}$(μSv·y^{-1})) (index w stands for worker and index BMTS, for working in the BMTS), 4 conventions were taken into consideration: (a) the spa personnel is working for 180 days annually, (b) according to the normal practice the worker stays for approximately 5 min during the filing process in the TR and additionally 5 min after the end of treatment for sanitising and arranging purposes, i.e., between 0–5 min and 40–45 min from start of filling, (d) the personnel follows filling, sanitising and arranging processes approximately 18 times per day. This convention is equivalent to working of 180 min–3 h within a TR and the remaining 300 min–6 h within the RR.

Hence, the additional Effective Dose $ED_{w,TR}$(μSv·y^{-1}) due to working in a TR, was calculated according to Eq. (3.7)

$$ED_{w,TR} = \left[CED\left(t = 0 \rightarrow t = \frac{5\ \mathrm{min}}{60\ \mathrm{min}\cdot h^{-1}}\right) + CED\left(t = \frac{40\ \mathrm{min}}{60\ \mathrm{min}\cdot h^{-1}} \rightarrow t = \frac{45\ \mathrm{min}}{60\ \mathrm{min}\cdot h^{-1}}\right)\right]\cdot 18d^{-1}\cdot 180d\cdot y^{-1} \tag{3.7}$$

The additional Effective Dose $ED_{w,RR}$ due to working within the RR, was calculated from Eqs. (3.1), (3.3), (3.4) and (3.5) accounting for the total additional total time of stay within the RR (300 min–5 h per day for 180 working days annually). This dose was calculated according to Eq. (3.8)

$$ED_{\mathrm{w,RR}} = CED_{\mathrm{RR}}(t = 8\mathrm{h}) \cdot \frac{5\mathrm{h}}{8\mathrm{h}} \cdot 180\mathrm{d} \cdot \mathrm{y}^{-1} \tag{3.8}$$

where $\mathrm{CED_{RR}}$ is the Cumulative Effective Dose of a worker staying in the RR.

The additional Effective Dose of the working personnel was calculated from Eqs. (3.7) and (3.8):

$$ED_{\mathrm{w,BMTS}} = ED_{\mathrm{w,TR}} + ED_{\mathrm{w,RR}} \tag{3.9}$$

2.2.2.2. BS. The radiation dose from radon in water can be delivered due to inhalation and ingestion. For patients of the BS who receive potable programme, this radiation dose is delivered for the most part, to the stomach region i.e. it is equivalent stomach dose. To calculate the additional annual equivalent stomach dose ($\mathrm{ED_{p,BS}}$) ($\mu\mathrm{Sv} \cdot \mathrm{y}^{-1}$) of the patients receiving the potable programme in the BS (index p stands for patient and index BS, for receiving a drinking programme in the BS), the aforementioned fact was taken into consideration, namely that each patient receives annually 15 potable treatments under a daily consumption of a total of 1050 mL of spring water. This additional equivalent stomach dose was calculated according to Eq. (3.10)

$$ED_{\mathrm{p,BS}} = C_{\mathrm{w}} \cdot C_{\mathrm{r}} \cdot DCF_3 \cdot 15\mathrm{d} \cdot \mathrm{y}^{-1} \tag{3.10}$$

where C_{w} ($\mathrm{Bq} \cdot \mathrm{L}^{-1}$) is the average radon concentration in water, C_{r} ($\mathrm{L} \cdot \mathrm{d}^{-1}$) the daily water consumption rate of a patient and $\mathrm{DCF_3}$ ($\mu\mathrm{Sv} \cdot \mathrm{Bq}^{-1}$) a factor converting the radon activity in water to equivalent stomach dose. C_{r} was taken equal to 1.05 $\mathrm{L} \cdot \mathrm{d}^{-1}$(1050 $\mathrm{mL} \cdot \mathrm{d}^{-1}$ as aforementioned) and $\mathrm{DCF_3}$ is equal to 14.4 ($\mu\mathrm{Sv} \cdot \mathrm{Bq}^{-1}$) (EURATOM, 2001; Louizi et al., 2003).

On the other hand, the workers of the BS receive radiation dose from radon in water due to inhalation, i.e., its effective dose. To calculate the additional annual Effective Dose of a worker of the BS ($\mathrm{ED_{w,BS}}$ ($\mu\mathrm{Sv} \cdot \mathrm{y}^{-1}$)) (index w stands for worker and index BS, for working in the BS) Eq. (3.8) was employed however under the convention that the personnel is working for 8 h per day, instead of 5 h of the worker in the BMTS, and 180 days annually. Hence

$$ED_{\mathrm{w,BS}} = CED_{\mathrm{RR}}(t = 8\mathrm{h}) \cdot 180\mathrm{d} \cdot \mathrm{y}^{-1} \tag{3.11}$$

3. Results and discussion

Table 2 presents the measured radon content of spring waters of the investigated thermal spas. The concentration of radon in water samples collected from the bathtub taps ranged from (54 ± 10) $\mathrm{Bq} \cdot \mathrm{m}^{-3}$ to (126 ± 12) $\mathrm{Bq} \cdot \mathrm{m}^{-3}$ (99% Confidence Interval–CI). No particular differentiation was observed between the samples contained cold and those contained hot spring water. The corresponding radon concentration in potable water samples (BS) ranged between (128 ± 11) $\mathrm{Bq} \cdot \mathrm{m}^{-3}$ and (297 ± 25) $\mathrm{Bq} \cdot \mathrm{m}^{-3}$(99% CI). Comparing averages, the potable waters exhibit a tendency to present higher radon concentrations. However, the small size of the samples confines the statistical power of such a comparison. On the other hand, when comparing the weighted averages, the concentration of radon in potable water samples is significantly higher (*t*-test on weighted averages, $*p<0.001$) compared to the concentration of radon in water samples collected from the bathtub taps. The differentiation may be attributed to the two different thermal springs from which water is drained in the building of the spring and in the building of the municipal thermal spas.

Table 2
Radon content of thermal waters of the investigated spas of Loutraki.

i/i	Location	Properties	Radon concentration $\mathrm{Bq} \cdot \mathrm{L}^{-1}$
1	BMTS	Bath tap water (cold)	66 ± 15
2	BMTS	Bath tap water (cold)	101 ± 1
3	BMTS	Bath tap water (cold)	87 ± 20
4	BMTS	Bath tap water (hot)	126 ± 11
5	BMTS	Bath tap water (hot)	111 ± 10
6	BMTS	Bath tap water (hot)	54 ± 10
7	BMTS	Bath tap water (hot)	80 ± 22
8	BMTS	Storage tank water	126 ± 12
9	BS	Potable water (HS)	164 ± 14
10	BS	Potable water (HS)	179 ± 15
11	BS	Potable water (HS)	297 ± 25
12	BS	Potable water (LS)	128 ± 11
Average ± SD		Bath tap water	94 ± 64
		Potable water	192 ± 164
Weighted		Bath tap water	99.2 ± 0.4
(average ± SD)		Potable water	161.4 ± 0.4

The terms BMTS and BS correspond to the Building of the Municipal Thermal Spas and to the Building of the Spring. The terms HS represent the potable Heavy Source and Light Source respectively. The reported results are at the 99% confidence interval. The weighted averages ($\bar{A}_{\mathrm{w,weigted}}$) were calculated according to the relation $\bar{A}_{\mathrm{w,weigted}} = \frac{\sum_{i=1}^{N} \left(\frac{A_{\mathrm{w,i}}}{\sigma_{\mathrm{w,i}}^2}\right)}{\sum_{i=1}^{N} \left(\frac{1}{\sigma_{\mathrm{w,i}}^2}\right)}$ (Bevington, 1969), where $A_{\mathrm{w,i}}$ is the radon concentration in the water sample ($\mathrm{Bq} \cdot \mathrm{L}^{-1}$) and $\sigma_{\mathrm{w,i}}$($\mathrm{Bq} \cdot \mathrm{L}^{-1}$) is the corresponding standard deviation (99% CI) of $A_{\mathrm{w,i}}$. $N=8$ ($i=1$ up to $i=8$) for tap waters and $N=4$ ($i=9$ up to 12) for potable waters.

The measured radon concentrations in thermal waters of Loutraki spas vary; yet, all are within the range of measurements reported both for the Loutraki spas (Danali-Cotsaki and Margomenou-Leonidopoulou, 1993) and other spas in Greece (Kritidis and Angelou, 1986; Danali-Cotsaki and Margomenou-Leonidopoulou, 1993; Trabidou et al., 1996; Vogiannis et al., 2004a,b,c; Geranios et al., 2004; Vogiannis and Nikolopoulos 2008). The concentration range is comparable to the value range reported for some spas (e.g. Vaupotic and Kobal, 2001; Song et al., 2005; Zunic et al., 2006) but also divergent from the corresponding range reported for other spas (e.g. Szerbin, 1996; Soto and Gomez, 1999; Andrzej Przylibski, 2000; Hovarth et al., 2000; Radolic et al., 2005; Erees et al., 2006; Sakoda et al., 2007; Somlai et al., 2007). Noticeable high concentrations have been reported in a swimming pool at the Radenci area (Slovenia) (Vaupotic and Kobal, 2001).

To notice is that only 6 of the 14 thermal water samples presented concentrations below the proposed limit of 100 $\mathrm{Bq} \cdot \mathrm{L}^{-1}$ (EURATOM, 2001). According to this publication (EURATOM, 2001), no remedial action regarding the protection of the public against exposure to radon in drinking water supplies, should be required if the concentration is less than 100 $\mathrm{Bq} \cdot \mathrm{L}^{-1}$. On the other hand, action is justified from the radiation protection point of view, if the corresponding radon concentration exceeds 1000 $\mathrm{Bq} \cdot \mathrm{L}^{-1}$. Hence, the majority of the measured radon concentrations of the water samples at the Loutraki spas (8 samples out of 14) lie in the intermediate range. This fact is indicative of the radon potential of the springs that drain mineral water to the Loutraki spas and provides justifications for the need of the investigation of radiation burden of patients and personnel in these spas.

Figs. 2 and 3 present characteristic cases of radon and progeny transient activity concentration variations recorded by AG and EQF in the ambient air of three of the investigated TRs of the BMTS. The statistics of radon and progeny peaks from the whole dataset collected in the TRs and the RR of the BMTS are presented in Tables 3 and 4. As may be observed from Table 3, the investigated peaks presented a range of maximum and mean A_0 values as well as duration times. The peaks present also a variety of data regarding progeny peaks. This

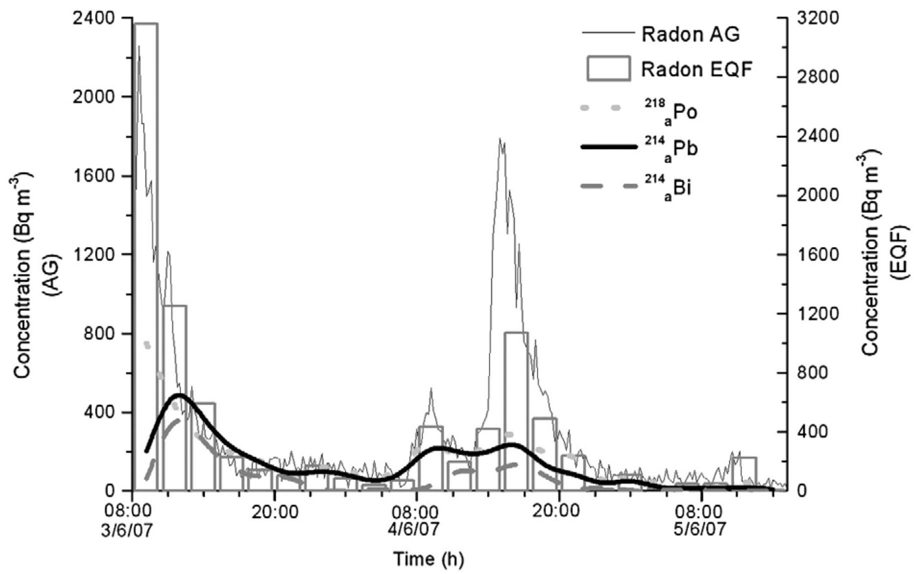

Fig. 2. First characteristic case of radon and progeny transient activity concentration variations recorded by AG and EQF in the ambient air of a TR of the BMTS. Only the attached progeny concentrations are presented for convenience.

diversity of data provides the opportunity of investigating the radiation protection issues and modelling within a range of corresponding values. The differences between the various detected radon peaks may be attributed to the differences in the level of the water in the bathtub after the end of the filling procedure. Generally, lower bathtub water levels lead to lower peak concentration values. Noticeable is the second peak of Fig. 3. This peak was detected through beginning of a, so called, "Jacussi" programme available for the bathtubs, however, by not emptying the bath. This programme generated continuously, via a mechanical system, a great amount of bubbles in the bathtub water. By applying Eqs. (1.1)–(1.2) to the peak radon concentrations recorded by AG (peak 1 1040 ± 130, peak 2 664 ± 90) for the 20 h meantime between these two peaks and for A_0 equal to $1040 \pm 130\ \mathrm{Bq \cdot m^{-3}}$, $\bar{A}_e$ equal to $0\ \mathrm{Bq \cdot m^{-3}}$, a_{eq} equal to $0\ \mathrm{m^{-1}}$, considering that the 20 h meantime is enough for the full diminishing of a_{eq}, λ_V equal to $0.5\ \mathrm{h^{-1}}$, K_L equal to $4.2 \cdot 10^{-4}\ \mathrm{m \cdot h^{-1}}$ (Corbett et al., 1997; Calugaru and Crolet, 2002) and k equal to the value of 0.276 which corresponds to a temperature of 25 grad Celsius, the model predicts radon concentration of $630 \pm 100\ \mathrm{Bq \cdot m^{-3}}$. This fact implies that the recorded differences between these two peaks of Fig. 3 correspond to the decay of radon during the approximately one-day meantime reduced by physical ventilation. According to the aforementioned fact, the bubble generation of the "Jacusssi" programme leads to the release of the whole radon content diluted in the bathtub water. This is indicative of the fact that radon after release during peaking is re-diluted into the bathtub water influencing in this manner the equivalent surface (Vogiannis and Nikolopoulos, 2008). In addition, this implies additional radiation burden to the patient when receiving treatment with a Jacussi programme, mainly due to the continuous re-release of the radon diluted in the water of the bathtub. To notice is however, that the aforementioned re-release and re-dilution of radon was not observed under another a focused experiment employing AG and EQF simultaneously, with all windows and the door closed and the mechanical ventilation switched off. In

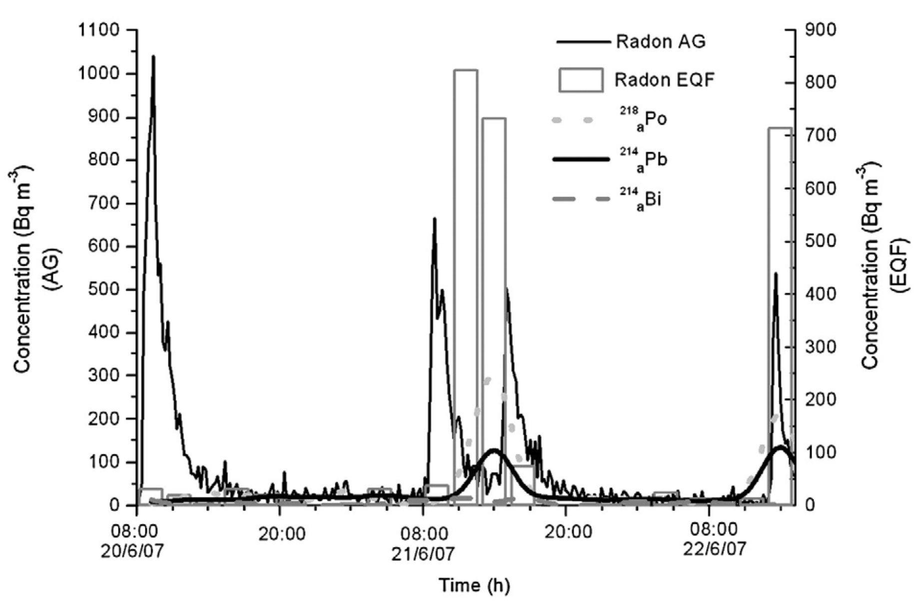

Fig. 3. Second characteristic case of radon and progeny transient activity concentration variations recorded by AG and EQF in the ambient air of a TR of the BMTS. Only the attached progeny concentrations are presented for convenience.

Table 3
Statistics of peak data recorded by AG.

Number of peaks	$\bar{A}_e$ range (Bq·m^{-3})	Range of maximum A_0 (Bq·m^{-3})	Range of A.M. A_0 (Bq·m^{-3})	Skewness range	Kurtosis range	Peak duration range (h)	Filling duration (min)	a_{fc} (m^{-1})
30	10–30	500–2500	200–1200	0.38–1.53	3.30–4.03	3–10	10	0.269

The peak data were collected from the investigated Treatment Rooms of the Building of the Municipal Thermal Spas. A.M. represents the arithmetic mean.

this experiment the bathtub was filled very slowly from the base by the use of an elastic tube of 2 m long. No transient concentration peaks were recorded, either for radon or progeny. The average recorded radon concentration in the TR was found equal to (220 ± 70) Bq·m^{-3}. Hence, it could be the generation of bubbles during filling that may provide explanations for the generation and the transient peaking of the equivalent surface a_{eq}.

Elevated indoor radon (>1000 Bq·m^{-3}) and progeny activity peak concentrations were detected (Figs. 2 and 3, Table 4). This seems to be in accordance to the radon potential of the spring waters of these spas (Table 2), as detected out of the measurements of their thermal waters. The detected radon and progeny peak concentrations are comparable in terms of magnitude and duration to similar peaks detected in the spas of Lesvos and Aidipsos (Vogiannis et al., 2004a,b, c; Geranios et al., 2004; Nikolopoulos and Vogiannis, 2007; Vogiannis and Nikolopoulos, 2008), as well as to those detected in other spas (Lettner et al., 1996; Szerbin, 1996; Soto and Gomez, 1999; Andrzej Przylibski, 2000; Hovarth et al., 2000; Vaupotic and Kobal, 2001; Song et al., 2005; Radolic et al., 2005; Erees et al., 2006; Zunic et al., 2006; Sakoda et al., 2007; Somlai et al., 2007). These are also comparable in terms of magnitude to the radon and progeny concentrations reported for some caves (Xinwei and Xiaolan, 2006; Vaupotic, 2008).

Even though AG and EQF were synchronised at the beginning of each experiment only some start peaks, as those of Fig. 2, were simultaneously recorded. For these cases the higher radon concentrations were recorded by EQF. Thereafter, the synchronisation was lost and EQF monitored averaged transient activity concentrations in respect to those recorded by AG. This loss could be attributed to the shifted timetable of the second bathtub emptying and filling (15:30) due to the closing time of the spa. Full synchronisation could be achieved only for independent experiments for which bathtub emptying and filling is done under a similar strict timetable as the one of the start peak of Fig. 2. However, even if a strict timetable is followed synchronisation may not be achieved as e.g. with the start peak of Fig. 3. In any case, differences in the recorded radon transient concentration peaks between AG and EQF may be explained by the differences in the followed measuring procedures.

Fig. 4 presents the results of the experimental determination of the time variations of the radon concentration of the bathtub spring water, as well as of the fitted power model curve of Eq. (1.2). The parameter d was found equal to (0.174 ± 0.005) (Fig. 4b Pearson correlation coefficient, $r^2 = 0.96$). This d value is (practically) equal to the corresponding one of the spas of Lesvos Island ($d = 0.17$, Vogiannis, 2005; Vogiannis and Nikolopoulos, 2008). This finding implies similarities between the Loutraki spas (BMTS) and the spas of Lesvos Island, regarding the modelling of the release of radon diluted in the spring water of the bathtub, to the ambient air. This result also entails analogous behaviour of the equivalent surface (Vogiannis and Nikolopoulos, 2008), as this is quantified through the estimation of the time variations of the parameter a_{eq}.

Fig. 5 presents graphically the results of the goodness-of-fit statistical tests for the modelled radon concentration (A_0) after applying model Eq. (1.1)–(1.2) to the collected radon peaks from the whole of the investigated TRs of the BMTS of the Loutraki spas. It may be observed that all fitted A_0 curves presented high adjusted r^2correlation coefficient values (Fig. 5a) in respect to the measured A_0 concentrations and thus, the fitted curve functions describe the measured data adequately. On the other hand, regarding the predictions of the model all peaks presented F values within the critical value range at the error probability of 1%. Hence, the time-series predicted and measured A_0 distributions of all investigated peaks present equal variances (Bevington, 1969; Press et al., 1992; Mendenhall and Sincich, 1994). The Pearson r^2correlation coefficient between predicted and measured A_0 values was found nearly 0.99 for all the investigated peaks, implying that the relation between predicted and measured A_0 values is highly linear, thus, the model predicts the measured data very well. For all the investigated peaks the Wilcoxon matched paired test Z value was well below the critical value, hence, the modelled and measured distributions are not right or left shifted (Mendenhall and Sincich, 1994). Similar results were found for all progeny peaks, i.e., A_i^u and A_i^a modelled concentrations according to Eqs. (2.1)–(2.9). However, these are not presented here for brevity.

Fig. 6 presents a characteristic case modelling of radon concentration (A_0) in a TR of the BMTS of the Loutraki spas ($i/i = 7$, Fig. 5). It may be observed that the model predicts acceptably well the measured data for a rather wide (kurtosis 1.75, skewness 0.48) peak as those basically found in the TRs of the BMTS of the Loutraki spas. A slight deviated prediction is observed at the beginning of this peak up to the first hour. This was also observed for some other peaks also. For these peaks, the modelled concentrations deviated during the first hour. According to Eqs. (1.1)–(1.2), this finding may be attributed to response of AG which is very quick (Genitron Instruments, 1998). Similar results were also detected for wide peaks in the spas of Lesvos Island (Greece) (Vogiannis and Nikolopoulos, 2008).

Table 4
Statistics of peak data recorded by EQF.

		Rn-222 (Bq·m^{-3})	Po-218 attached (Bq·m^{-3})	Po-218 unattached (Bq·m^{-3})	Pb-214 attached (Bq·m^{-3})	Pb-214 unattached (Bq·m^{-3})	Bi-214 attached (Bq·m^{-3})	Bi-214 unattached (Bq·m^{-3})	F-factor	PAEC (MeV·L^{-1})
BMTS	A.M. range	88–640	16–310	7–90	14–270	1–10	4–150	1–5	0.44–0.70	580–2560
(TR)	Max range	820–3160	350–1000	88–460	160–780	13–33	22–590	10–20	0.90–1.00	33–260,000
BMTS	A.M. ± S.D.	80 ± 30	21 ± 9	19 ± 16	17 ± 12	5 ± 3	8 ± 6	N.D.	0.21 ± 0.15	760 ± 320
(RR)	Value range	0–158	9–32	8–25	7–38	1–10	1–19	N.D.	0–0.28	250–1430
BS (RR)	A.M. ± S.D.	103 ± 77	33 ± 15	34 ± 19	29 ± 15	5 ± 3	13 ± 10	N.D.	0.19 ± 0.13	980 ± 590
	Value range	0–183	18–47	9–52	11–45	1–11	0–36	N.D.	0–0.28	340–1780

A.M. is the arithmetic mean, S.D. is the standard deviation and Max is the maximum recorded value. The peaks correspond to the data of Table 3 (30 peaks). The terms BMTS and BS correspond to the Building of the Municipal Thermal Spas and to the Building of the Spring. The term (TR) represents Treatment Room and the term (RR), Reception Room. N.D. stands for non detectable activity concentration. Since bath treatment is associated with the appearance of radon and progeny peaks, the ranges of maximum (i.e. peak) values are presented for the TRs of the BMTS. For the other two cases (RR of BMTS and BS) value ranges are presented.

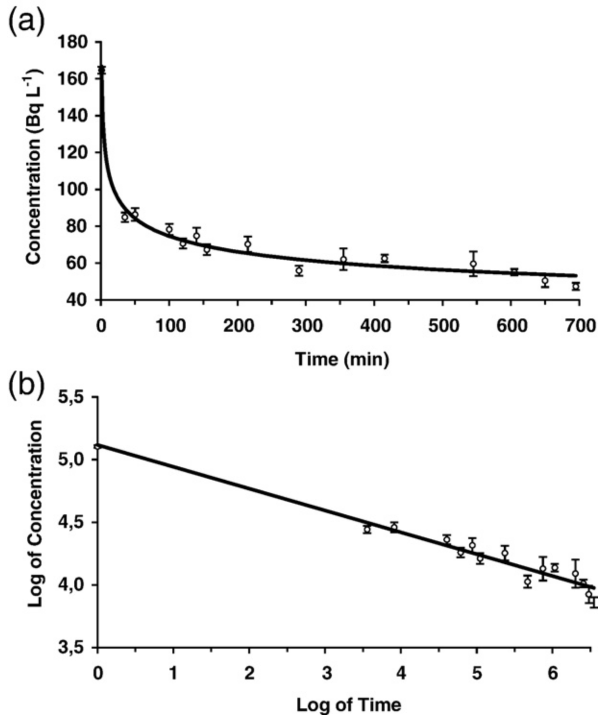

Fig. 4. (a) Measurements of the time variations of the radon concentrations of the bathtub spring water, (b) Fitted power model curve of Eq. (1.2) linearly transformed.

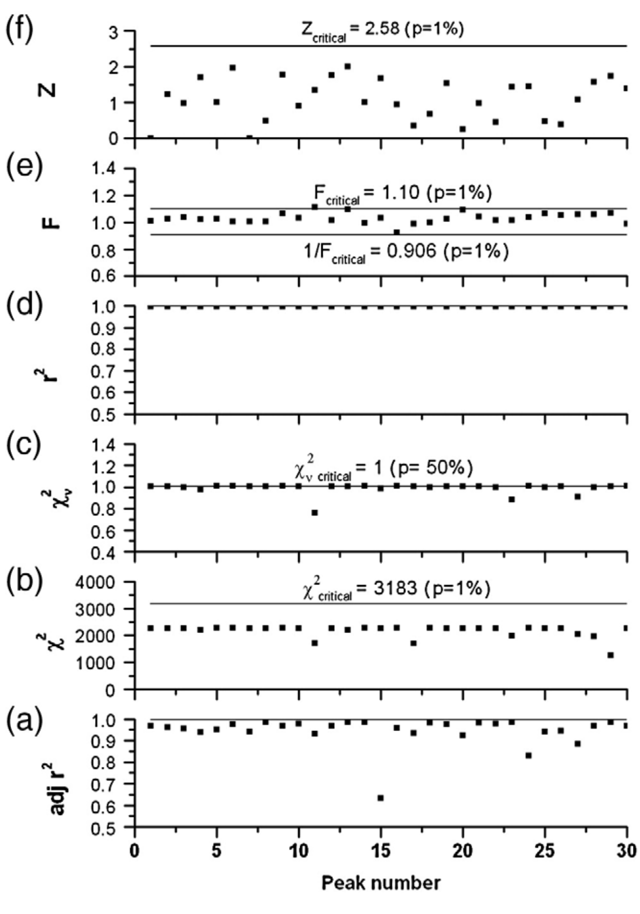

Fig. 5. Graphical presentation of the results of the goodness-of-fit statistical tests for the modelled radon concentration (A_0) after applying model Eqs. (1.1) and (1.2) to the collected radon peaks from the whole of the investigated TRs of the BMTS of the Loutraki spas.

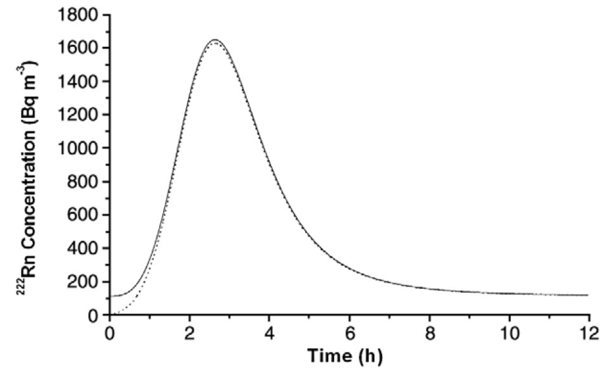

Fig. 6. Characteristic case of modelling of radon concentration (A_0) in a TR of the BMTS of the Loutraki spas ($i/i=7$, Fig. 5). The dotted curve refers to the fitted time-series A_0 functions of AG. The other curve refers to the modelled A_0 data.

Fig. 7 presents the variations of the specific total interfacial area (a_{eq}) of Fig. 6 obtained from the modelling according to Eqs. (1.1) and (1.2). A central positive symmetric peak and a negative peak can be observed in the temporal variations of a_{eq}. For the first 2 h, a_{eq} increases up to the value of 24 m^{-1} and then decreases down to 0.73 m^{-1}. Similar results were obtained for the other peaks of the BMTS of Loutraki spas yet these are not presented here for brevity. It should be mentioned that, some a_{eq} peaks were sharper and some others presented a negative peak of higher or lesser degree. Since, positive values correspond to radon release and negative values to radon re-dilution, the detected radon peaks in the BMTS of the Loutraki spas, could be attributed to the peaks of the variations of a_{eq}. The positive peak of a_{eq} may be attributed to the release of radon and dispersed water droplets in the TR, both arising, mainly, during the bathtub filling (please see e.g. related publication (Vogiannis and Nikolopoulos, 2008) and, at a lesser degree, after the end of the filling procedure. Yet, given the fact that radon re-dilution was detected after switching on the "Jacussi" programme, this re-dilution could be attributed to the negative variations of a_{eq}. Noticeable is the fact that the value of 24 m^{-1} corresponds to a large surface, since this value corresponds to an area which is 24 times greater than value of the volume of the TR. A possible explanation for this large surface could be obtained on the basis of the great amount of hydro-droplets which are released during the first 4 h from the beginning of the bath treatment. This fact was also observed in other spas in Greece (Vogiannis et al, 2004a,b,c; Geranios et al., 2004). This is re-enforced by the relative humidity measurements. As was systematically observed, the relative humidity in the TRs ranged from 85% to 95% during the first 4 h, whereas, this was below 75% thereafter.

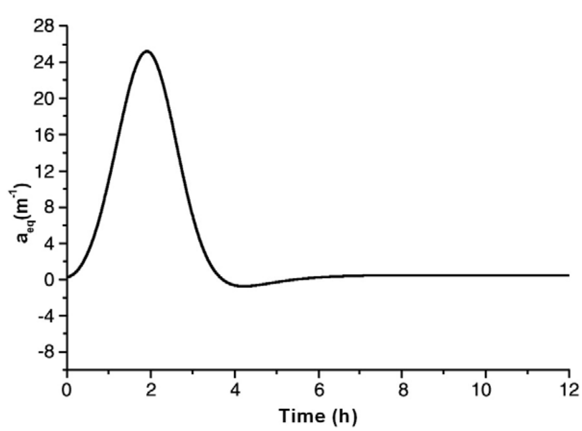

Fig. 7. Variations of the specific total interfacial area (a_{eq}) of Fig. 6 obtained from the modelling according to Eqs. (1.1) and (1.2).

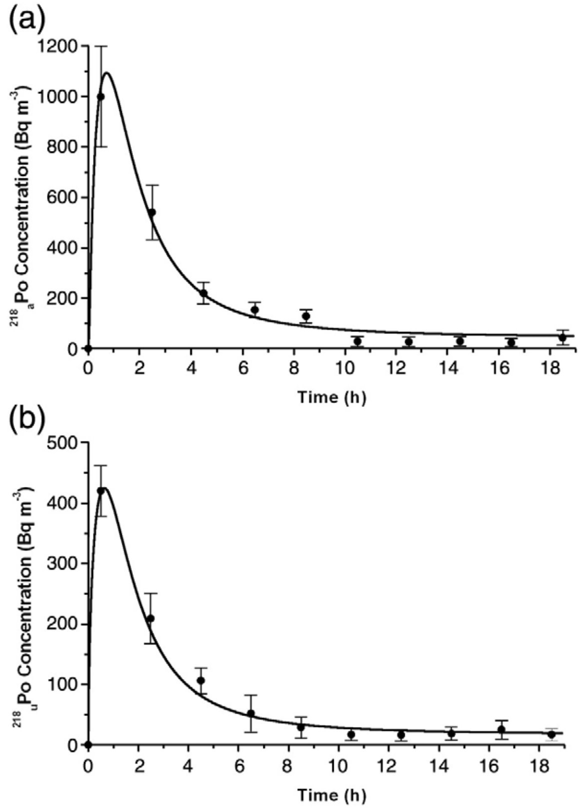

Fig. 8. Measurements and predictions of model Eqs. (2.1)–(2.9) for the TR of Fig. 6 for (a) ${}^{218}_{a}$Po and (b) ${}^{218}_{u}$Po.

Fig. 8 presents two characteristic cases of predictions of model Eqs. (2.1)–(2.9) for ^{218}Po attached and unattached progeny for the TR of Fig. 6. The model predicts acceptably well the measured ^{218}Po concentrations for Fig. 6 (e.g. $F=1.01$ and $z=1.98$). Similar findings were also found in all investigated TRs and for all progeny. These are not presented here for brevity. There have been observed modelled progeny peaks with outliers. However, in all cases these were very few. The modelled progeny concentrations of Fig. 8 present also peaks which may be attributed to the bath filling procedure.

Table 5 summarises the results of the parameters $\lambda_{a,i}$, $\lambda^{a}_{d,i}$ and $\lambda^{u}_{d,i}$ which were obtained after running the model Eqs. (2.1)–(2.9). Table 5 also presents the ranges of the abovementioned model parameters for changing ventilation rate values. To estimate these ranges, 30 iterative solutions of the model Eq. (2.1)–(2.9) were performed, allowing the ventilation rate values (λ_v) to vary in ascending order from -10% to $+10\%$ (this percentage range was arbitrarily selected) in respect to the measured values. Similar analysis was performed in a previous paper (Nikolopoulos and Vogiannis, 2007). The iterative solutions and the estimation of the parameters $\lambda_{a,i}$, $\lambda^{a}_{d,i}$ and $\lambda^{u}_{d,i}$ were performed in accordance to the methods described earlier in text however, considering the measured progeny time-series data unchanged. Ventilation rate changes affects $\lambda_{a,i}$, $\lambda^{a}_{d,i}$ and $\lambda^{u}_{d,i}$ values in a non linear manner. This fact was expected, since (according to system Eq. (2.1)–(2.9)) the aforementioned parameters are combined in a non linear manner with ventilation rate. However, a change of $\pm 10\%$ (20% range change) in ventilation rate imposes lower relative deviation in the range of the above model parameters (e.g. from 6% for $\lambda^{a}_{d,1}$ to 18% for $\lambda_{a,3}$). These values are in the corresponding value range reported by a previous publication (Vogiannis and Nikolopoulos, 2008). The values are also within the value range which could be estimated (Nikolopoulos and Vogiannis, 2007) by related values (e.g. diffusion constant) reported by others (Nazaroff and Nero, 1988; Datye et al., 1997).

Table 5
Estimated model parameters $\lambda_{a,i}$, $\lambda^{a}_{d,i}$ and $\lambda^{u}_{d,i}$ for the BMTS of the Loutraki spas.

	$\lambda_{a,i}$ (h^{-1})		$\lambda^{a}_{d,i}$ (h^{-1})		$\lambda^{u}_{d,i}$ (h^{-1})	
	A.M.	Range	A.M.	Range	A.M.	Range
$i=1$ Po-218	40	43–48	1.5	1.5–1.6	46	45–51
$i=2$ Pb-214	106	103–112	1.5	1.4–1.6	12	11–13
$i=3$ Bi-214	11	10–11	0.50	0.47–0.51	0.30	0.29–0.32

Ranges were estimated for varying ventilation rate values (please see text also). Index i equals 1, 2, 3 for ^{218}Po, ^{214}Pb and ^{214}Bi respectively. A.M. represents the arithmetic mean of the corresponding Levenberg–Marquardt fit values.

Table 6 presents the dosimetric estimations from the whole data set. The effective doses estimated for the patients receiving bath treatments ($ED_{p,BMTS}$) are not high. All values are below the accepted limits for the general population (UNSCEAR, 2000). However the effective doses are not negligible, since they are comparable to the national average effective dose value of (0.09 ± 0.04) mSv·y^{-1} due to radon in Greece (Nikolopoulos et al., 2002). On the other hand, the corresponding doses for personnel of the BMTS ($ED_{w,BMTS}$) are higher, but below the accepted limit for workers of 20 mSv·y^{-1} (ICRP, 1993). Similar to the effective doses of working personnel of the BMTS, are the corresponding doses of the personnel of the BS, however, rather lower. This could be attributed to the fact, that the personnel of the BS is just residing in the RR without being additionally exposed to extra sources of radon (e.g. bathing in TRs). Noticeably high, are the annual effective stomach doses received by the patients of the BS. Yet the estimated stomach doses are lower than the limit of 150 mSv·y^{-1} (ICRP, 1993; UNSCEAR, 2000; http://www.euronuclear.org/info/encyclopedia/r/ radiation-exposure-dose-limit.htm). This is reinforced by the aforementioned facts, namely that the radon content of the springs of the BS is below the proposed limit of 100 Bq·L^{-1} (EURATOM, 2001) and that all the measured water samples in the BS lie in the intermediate range. Worth to notice is the fact that that the upper bound estimation of annual dose to a worker (12 mSv) is over half the occupational limit.

The effective dose values of the patients of the BMTS, together with the presented data of Figs. 2 and 3, indicate a short-term radiation burden both for bathers and working personnel which is delivered mainly while these reside in a TR of a spa. All dose estimations in the BMTS are biased by the variability imposed by the differentiations in the level of filling of the bathtub, the preferences of the patients of the BMTS regarding the opening of the windows, the possible switching-on of the mechanical ventilation, the mixing of spring and non-spring water and the variations of the activity concentrations in ambient air. They are also biased by the different ambient atmospheres found in the investigated RRs and TRs studied compared to the standard

Table 6
Dosimetric estimations for the spas of Loutraki.

Spa		x and equation		ED_x (μSv·y^{-1})	Value range
BMTS (TR)	Patient	$x=p$, BMTS	Eq. (3.6)	183	14–444
BMTS (TR)	Working personnel	$x=w$, TR	Eq. (3.7)	4940	385–12,000
BMTS (RR)	Working personnel	$x=w$, RR	Eq. (3.8)	200	11–288
BS (RR)	Patient	$x=p$, BS	Eq. (3.10)	43,500	29,000–67,400
BS (RR)	Working personnel	$x=w$, BS	Eq. (3.11)	901	145–1650
$ED_{p,BMTS}$ (μSv·y^{-1})				183	14–444
$ED_{w,BMTS}$ (μSv·y^{-1})				5140	11–12,000
$ED_{p,BS}$ (μSv·y^{-1})				43,500	29,000–67,400
$ED_{w,BS}$ (μSv·y^{-1})				901	145–1650

The data for the BMTS were estimated from Table 4. The data for the BS were estimated from Table 2. Symbols are given in Section 2.2.2. Indication: x represents the various indexes of Eqs. (3.6), (3.7), (3.8), (3.10) and (3.11) respectively. The values of $ED_{p,BS}$ refer to equivalent stomach dose (Eq. (3.10)). All other values refer to Effective Doses.

atmosphere conditions proposed in the literature (Porstendörfer, 2001) and by the differentiation in the definition of the unattached fraction in terms of PAEC given in the above publication. Based on the instrumentation available, this definition was considered as the best approximation. Moreover, they are affected by the multiple model parameters ($\lambda_{a,i}$, $\lambda^{a}_{d,i}$, $\lambda^{u}_{d,i}$ and λ_v). However, as discussed earlier in text (Table 5) the changes in ventilation rate imposes lower relative deviation in the range of the above model parameters model parameters (λ_v, $\lambda_{a,i}$, $\lambda^{a}_{d,i}$ and $\lambda^{u}_{d,i}$). However, as it was observed from various runs, the ventilation rate affects effective doses significantly. For instance, a $\pm 1\%$ change in λ_v induces about 30–40% change in peak effective dose estimations. Similarly, bias in some model parameters affects model predictions significantly. For instance, the percentage for $\lambda^{a}_{d,1}$ is about 9 times and for $\lambda^{u}_{d,1}$ 28 times in percentage. On the other hand, other parameters (e.g. $\lambda_{a,3}$) have little influence on model estimations and, hence, on dose estimations.

As a conclusion, treatment and working in the Loutraki spas leads to intense variations of radon and progeny and consequently impose additional radiation burden to patients and personnel. In the sense of the directive 96/29/EURATOM (CEC, 1996), the estimation of this burden for the BMTS and the BS is of significance regarding radiation doses due to bathing and water drinking in spas. In this paper, this estimation was based on measurements and modelling of radon and progeny. The use of recently (2007 and 2008) published models for the estimation of dose, is a completely new perspective. In addition, it enabled the calculation of recently proposed parameters for thermal spas, such as the range values of $\lambda_{a,i,}$ $\lambda^{a}_{d,i}$ and $\lambda^{u}_{d,i}$, the experimental determination of the time variations of the radon concentration of the bathtub spring water and the related parameter d and the calculation of variations of the specific total interfacial area a_{eq}. All these parameters ($\lambda_{a,i,}$ $\lambda^{a}_{d,i}$, $\lambda^{u}_{d,i}$, d and a_{eq}) are under investigation and are essential elements in explaining the variations of radon and progeny during bath treatment. Moreover, they provide additional information on the role of water in the generation of radon and progeny peaks. This role was experimentally investigated through the experiment of Fig. 4. The findings of Fig. 4 are new and assist the effort of better understanding radon and progeny peaking. In the above consensus, more effort may be put in this field in future. It should be mentioned however, that such treatments may eventually impose positive results to the every-day life of the people using thermal spas.

Acknowledgment

This paper is dedicated to a beloved person, Mrs. Anna Orfanou, secretary of the Physics Department of the Technological Institution of Piraeus, who lost her struggle with cancer after five years.

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