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Radon continuous monitoring in Altamira Cave (northern Spain) to assess user's annual effective dose

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Abstract

In this work, we present the values of radon concentration, measured by continuous monitoring during a complete annual cycle in the Polychromes Hall of Altamira Cave in order to undertake more precise calculations of annual effective dose for guides and visitors in tourist caves. The ^{222}Rn levels monitored inside the cave ranges from 186 Bq m^{-3} to 7120 Bq m^{-3}, with an annual average of 3562 Bq m^{-3}. In order to more accurately estimate effective dose we use three scenarios with different equilibrium factors ($F=0.5$, 0.7 and 1.0) together with different dose conversion factors proposed in the literature. Neither effective dose exceeds international recommendations. Moreover, with an automatic radon monitoring

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system the time remaining to reach the maximum annual dose recommended could be automatically updated.

Keywords: Effective dose; Cave environment; Radon concentration; Dose conversion factor; Show cave

1. Introduction

Radon is an odourless and colourless radioactive noble gas. It emanates from soil, rock, sediments and water, and produces decay products in air. It is the greatest source (69%) of natural radioactivity. Prolonged exposure to radon may cause a negative effect on our health. In fact, a high concentration of radon gas is recognized as causing lung cancer and bronchial tissue damage, as has been found in studies from uranium mines (reviewed in Qureshi et al., 2000; Yamada, 2003). Radon monitoring at highly radioactive locations such as underground mines or caves, is important to assess the radiological hazards to occupational workers and occasional visitors.

Previous studies have been conducted by diverse research groups to investigate radon concentrations in cave systems, and relate these to health implications for occasional users (such as visitors in show caves), cavers and cave workers, such as guides (Duffy et al., 1996; Hakl et al., 1997; Dueñas et al., 1999; Gillmore et al., 2000, 2001, 2002; Sperrin et al., 2000). The obtained results show that radon levels in several of the studied caves can pose a risk for the health of workers and visitors. Recently, Sperrin et al. (2000) demonstrated that these results may have even underestimated the risk, because radon concentration reported in some papers revealed a higher concentration when the site was revisited, and more precise data were obtained by means of new methodologies and measurement strategies. Radon levels in karstic systems depend on a complex interrelation of different factors, both external and internal (Kies et al., 1997): outside–inside temperature differences, wind velocity, atmospheric pressure variations, humidity, karstic geomorphology and porosity and radium content of the sediments and rocks. The complex dynamics of radon in natural underground atmospheres makes continuous monitoring useful and even necessary for radioprotection purposes in show caves.

In this work, we present the values of radon concentration, measured by continuous monitoring during a complete annual cycle (February 1997–January 1998) in the Polychromes Hall of Altamira Cave. Previous researchers measured the ^{222}Rn concentration in the cave by means of periodic air sampling, focused on calculating exposure levels (Fernández et al., 1984) or ventilation rates in the cavity (Fernández et al., 1986). This work documents the importance of continuous short-term radon monitoring to perform the correct calculations of annual effective dose for guides and visitors in tourist caves.

Using the ICRP (1994) recommendations, European Communities (EC, 1990) and Spanish Government (Real Decreto 783, 2001) normative, the annual effective dose for workers should not exceed 20 mSv and for occasional users (as visitors) should not exceed 1 mSv.

1.1. Altamira cave

The Altamira Cave is world-famous for possessing a remarkable collection of Palaeolithic rock paintings and engravings. Since its discovery at the end of the 19th century, it has aroused considerable archaeological interest due to its famous polychromatic paintings located on the roof of the Polychromes Hall. The paintings date back approximately 15 000 years (Valladas et al., 1992). Today, the dimensions of this hall have decreased to a volume of 326 m^3, with an inner surface of 150 m^2 and an average height of 2.4 m.

The Altamira Cave is located near Santander (Santillana del Mar, northern Spain) very close to the Atlantic Ocean (5 km). The cave consists of a series of rooms and S-shaped passages (Fig. 1) with a total length of 270 m. It is a downward-trending cave located in the upper part of a small calcareous hill, which stands at an altitude of 156 m above sea level. The cave is located in the unsaturated water zone of a tabular polygenic karst system. In this karst zone, the so-called senile area, the processes of dissolution/destruction are more important than the precipitation/lithochemical reconstruction processes (Hoyos, 1993; Sánchez-Moral et al., 1999). The cave has developed in Cretaceous calcarenitic limestones. These limestones are fossiliferous packstone-grainstones, which are partly dolomitized.

2. Methodology

2.1. Radon measurement

A micro-environmental monitoring system was installed in the cave to record the microclimate inside and outside the Polychromes Hall (described in Sánchez-Moral et al., 1999). The ^{222}Rn concentration was measured by means of a Pylon AB5 scintillometer with a CPRD (Continuous Passive Radon Detector). This equipment is calibrated periodically with a ^{222}Rn calibration standard cell model Pylon 3150[a]. An automatic recording system was programmed to store records every hour during the entire annual cycle. As a complementary record, etched track type commercial detectors (Landauer RadTrack) were used for measurements over a longer period, with an integration period of one month.

2.2. Dose calculation

Several methods have been reported to calculate the dose of radon concentration received by a person in an underground environment, most of them developed

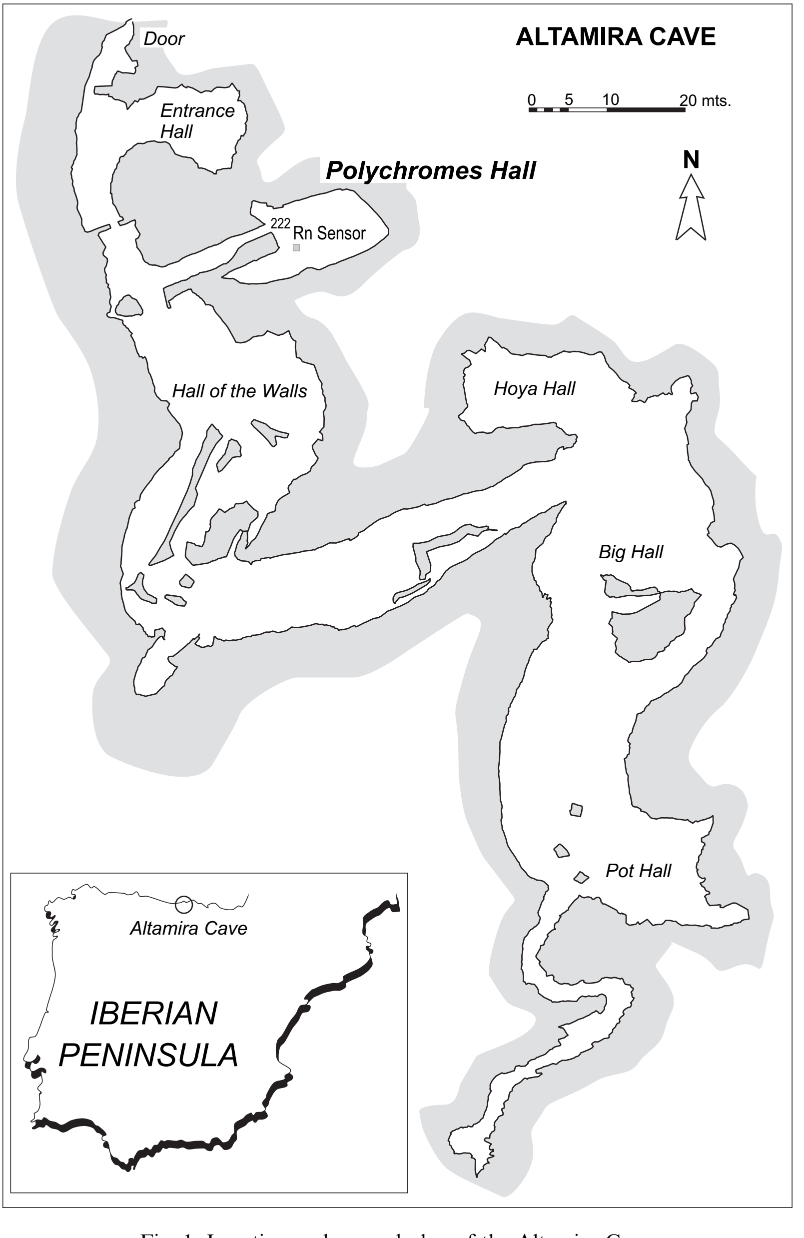

Fig. 1. Location and ground plan of the Altamira Cave.

during studies related to the health problems of mineworkers (Denman and Parkinson, 1996; Qureshi et al., 2000; Furuta et al., 2002).

Denman and Parkinson (1996) designed a method of estimating radiation dose from radon concentration as

$$\text{Dose (mSv)} = \frac{\text{concentration}\ (\text{Bq m}^{-3}) \times \text{duration}\ (\text{h})}{126\,000}$$

The method was applied in caves and abandoned mines in England (Gillmore et al., 2000, 2001, 2002; Sperrin et al., 2000), with some conditionings: the dose was calculated using the relation that 1 mSv is equivalent to 126 kBq m^{-3} h, which is derived from analysis by the NRPB (Wrixon et al., 1988), and the relation that 10 mSv is equal to 1 Working Level Month (WLM) (ICRP, 1986), assuming an equilibrium factor (F) of 0.5 (after Gillmore et al., 2002).

The International Commission for Radiological Protection (Publication 65, ICRP, 1994) recommends the use of a single factor (1425 mSv/(J h m^{-3}) or 5 mSv/WLM), determined from uranium mining epidemiological studies, as the preferred method to convert radon progeny exposure into effective dose of radon. The ICRP recognized that differences in aerosol conditions could modify the dose conversion factor, but considered the epidemiological approach to be simpler and more direct than the alternate dosimeter modelling approach (Solomon, 2001). Moreover, Porstendörfer (2002) explained that, caused by the different aerosol conditions concerning particle number concentration and activity size distribution, the dose conversion factor (DCF) of the radon progeny (in living and working places) varies between 4.2 and 11.5 mSv/WLM. In homes and at workplaces with a high particle concentration ($>6\times10^4$ particles/cm^3, areas with additional aerosol sources), the DCF-values range between 4.2 and 7.1 mSv/WLM. In the case of "normal" aerosol conditions in homes, at workplaces and outdoors, the dose values of these places are significantly higher. The DCF-values vary between 8.0 and 11.5 mSv/WLM.

Moreover, detailed studies of equilibrium between ^{222}Rn and radon progeny concentrations within limestone caves indicated that equilibrium factors vary from 0.04 to 0.95 with a mean value of about 0.5, which is the one used in some studies (Hyland and Gunn, 1994; Madden, 1997; Gillmore et al., 2000, 2001). Solomon et al. (1992) reported values in Australian caves with equilibrium ratios of between 0.36 and 0.52 with 0.4 on average. Duffy et al. (1996) found in caves in Ireland that F values ranged from 0.12 to 0.71 and varied both within and between caves. Gillmore et al. (2001) note that in mines in the Southwest of England preliminary surveys suggested F values of between 0.17 and 0.4.

In order to calculate the effective dose affecting both tour guides and visitors using different scenarios of F and DCF, we used the method proposed by Qureshi et al. (2000) that calculates annual WLM (Working Level Month) exposure as:

$$\text{WLM} = \frac{\text{Bq m}^{-3} \times F \times t}{3700\ \text{Bq m}^{-3}\ \text{per WL} \times 170\ \text{h per WM}}$$

where Bq m^{-3} is the radon level measured in a cave, F is the equilibrium factor and t is time spent in the cave over a year. Because a record of monthly radon levels and hours spent inside the cave by tour guides is available, we calculated the WLM as follows:

$$\mathrm{WLM} = \frac{\sum\left(\mathrm{Bq\ m^{-3}} \times F \times t\right)_{\mathrm{m}}}{629\ 000}$$

where $(\mathrm{Bq\ m^{-3}} \times F \times t)_{\mathrm{m}}$ is the proportional WLM per month.

3. Results and discussion

Data about ^{222}Rn concentration in the cave atmosphere from February 1997 to January 1998 are shown in Fig. 2. The radon levels monitored inside the Polychromes Hall ranges from 186 Bq m^{-3} to 7120 Bq/m^3, with an annual average of 3562 Bq m^{-3}. In order to simplify the 8587 data points, monthly statistics were calculated (Table 1 and Fig. 2). On the whole, the variation of the radon concentration during year measured in real time is in agreement that obtained by means of etched track radiometers, although the values obtained by these last detectors are slightly lower than those obtained by means of the continuous monitoring. Also, the monthly averages calculated from the values monitored continuously during 1997 show a variable trend of the concentration, similar to the one obtained by Fernández et al. (1986) in 1983 by means of weekly air sampling. This coincidence demonstrates the micro-environmental stability of karstic systems

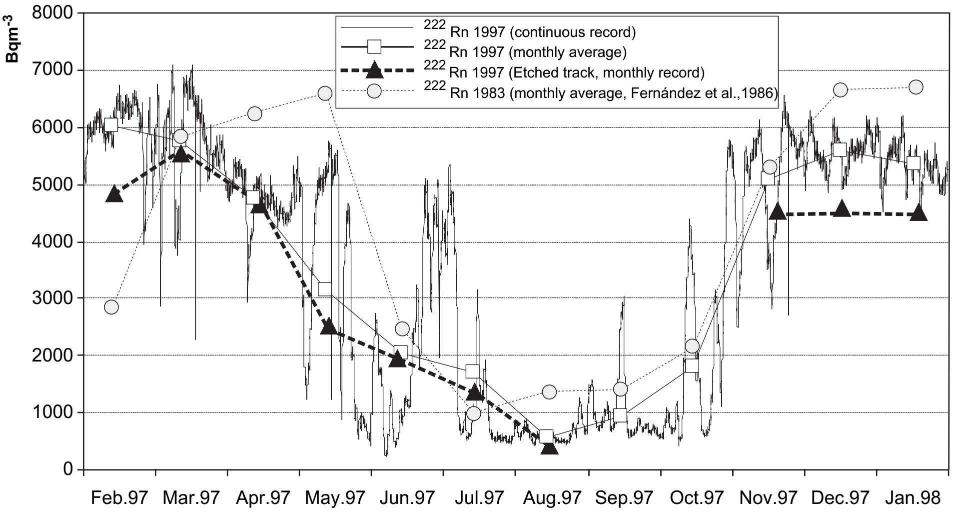

Fig. 2. ^{222}Rn concentration in Altamira Cave from February 1997 to January 1998 (continuous monitoring and monthly average) and comparison with radon concentration measured in 1983 by Fernández et al. (1986).

Table 1
^{222}Rn concentration in Altamira Cave

Month	Continuous measurement			Etched track
	Bq m^{-3} (median)	Bq m^{-3} (min.)	Bq/m^{-3} (max.)	Bq/m^{-3}
Feb. 97	6026	3938	6758	4810
Mar. 97	5756	2244	7120	5602
Apr. 97	4738	2909	5497	4847
May 97	3162	450	5772	2427
Jun.97	2053	186	5109	1857
Jul. 97	1694	399	5360	1262
Aug. 97	574	362	1229	303
Sep. 97	940	501	3018	–
Oct. 97	1798	353	5734	–
Nov. 97	5079	2455	6587	4466
Dec. 97	5596	4853	6316	4488
Jan. 98	5357	4515	6218	4499
Annual mean	3562	186	7120	3456

such as the Altamira Cave (Sánchez-Moral et al., 1999). The main differences are in the concentrations measured during the month of February, which can be related to the different methodologies used since the periodic sampling can coincide with short stages of high ventilation, as is the case of the end of the winter, and lead to anomalous data.

Fernández et al. (1984) calculated radiation exposure levels in Altamira from radon values recorded during a measurement campaign that covered all of 1981. They calculated exposure levels for a guide working in the cave for an average of 170 h month^{-1} over 11 months yr^{-1} (that was the situation before the cave was closed to visitors in 1976) and for 15 h month^{-1} over 11 months yr^{-1} (the usual time spent inside the cave by guides after 1976). Exposure levels were measured as pCi/l, and we have transformed these reading to WLM using the equivalence of 68 000 pCi/l = 4 WLM as proposed by Fernández et al. (1984). Before 1976, exposure levels during periods of high radon concentration were 17.6 WLM and during periods of low radon concentration was 1.65 WLM. For 1982 (less time inside the cave) exposure levels were 1.55 and 0.145 WLM, respectively. Exposure levels are calculated using the same methodology with maximum and minimum annual average radon levels found in this study. Using 170 h month^{-1} during 11 months yr^{-1} values obtained are 21.16 WLM and 0.55 WLM, respectively. Using 15 h month^{-1} over 11 month yr^{-1} the values are 1.87 WLM and 0.049 WLM, respectively. Due to the lack of data obtained in continuous monitoring, the maximum and minimum concentrations were not taken into account in that study. Considering the maximum values and the times spent inside the cave, prior to closing in 1976, the annual effective dose affecting a cave guide could surpass the levels recommended by ICRP and European authorities.

To estimate the effective dose it is necessary to know the time spent in the cave by users (in this case visitors and tour guides). In our study, the record of monthly and

Table 2
WLM calculated for tour guides and visitors to the cave using $F=0.5$

Month	Tour guide				Visitor (20 min in cave)		
	Time[a]	Med. WLM	Min. WLM	Max. WLM	Med. WLM	Min. WLM	Max. WLM
Feb. 97	36	0.172	0.113	0.193	0.002	0.001	0.002
Mar. 97	38	0.174	0.068	0.215	0.002	0.001	0.002
Apr. 97	27	0.102	0.062	0.118	0.001	0.001	0.001
May 97	4	0.010	0.001	0.018	0.001	0.000	0.002
Jun.97	22	0.036	0.003	0.089	0.001	0.000	0.001
Jul. 97	54	0.073	0.017	0.230	0.000	0.000	0.001
Aug. 97	66	0.030	0.019	0.064	0.000	0.000	0.000
Sep. 97	51	0.038	0.020	0.122	0.000	0.000	0.001
Oct. 97	26	0.037	0.007	0.119	0.000	0.000	0.002
Nov. 97	10	0.040	0.020	0.052	0.001	0.001	0.002
Dec. 97	0	0.000	0.000	0.000	0.001	0.001	0.002
Jan. 98	15	0.064	0.054	0.074	0.001	0.001	0.002
All year	349	0.776	0.385	1.296			
Annual[b]	349	0.995	0.052	1.988	0.001	0.000	0.002

[a] Time spent in cave per month (tour guide with more working hours accumulated).
[b] Using annual mean of radon level of 3562 Bq m^{-3}.

annual time spent within the cave by tour guides is available and presented in Table 2. Visitors spent 20 min within the cave, and because the waiting list to visit the cave is quite long it is not usual that same person visit the cave more than once per year. In the same way, as explained previously, it is necessary to take into consideration the equilibrium factor (F). We have applied the equilibrium factor of 0.5 used in different mines and natural cave systems (Gillmore et al., 2000, 2001; Sperrin et al., 2000) and show caves (Gillmore et al., 2002), and we have also calculated doses using $F=0.7$ and $F=1.0$, representing the worst and intermediate scenario, respectively. Both WLM exposures to tour guides and visitors are summarized in Tables 2–4.

As can be observed in Tables 2–4, in all scenarios the median and maximum values calculated taking into account the annual mean radon level are higher than the annual values estimated using monthly means of radon level and hours spent inside the cave during the same month. This emphasizes the importance of accurately recording the time and date spent in the cave by workers and use, in all calculations of the proportional WLM exposure per month. Shorter periods, such as weekly or daily WLM exposure, can also be calculated. In this case, the real-time available record is more precise than data calculated using annual averages. Previous researchers found several significant differences between calculated annual WLM exposures and those measured directly by means of dosimeters (Duffy et al., 1996) which could be explained by the use of annual averages to perform the calculations.

Using "year round" accumulated values, in three scenarios ($F=0.5$; $F=0.7$ and $F=1.0$) the differences between minimum and maximum values are substantial. Annual WLM values for tour guides ranges from 0.385 to 1.296 using $F=0.5$, from 0.539 to 1.814 using $F=0.7$ and from 0.769 to 2.592 using $F=1.0$. Consequently, it is

Table 3
WLM calculated for tour guides and visitors to the cave using $F = 0.7$

Month	Tour guide				Visitor (20 min in cave)		
	Time[a]	Med. WLM	Min. WLM	Max. WLM	Med. WLM	Min. WLM	Max. WLM
Feb. 97	36	0.241	0.158	0.271	0.002	0.001	0.002
Mar. 97	38	0.243	0.095	0.301	0.002	0.001	0.003
Apr. 97	27	0.142	0.087	0.165	0.002	0.001	0.002
May 97	4	0.014	0.002	0.026	0.001	0.000	0.002
Jun.97	22	0.050	0.005	0.125	0.001	0.000	0.002
Jul. 97	54	0.102	0.024	0.322	0.001	0.000	0.002
Aug. 97	66	0.042	0.027	0.090	0.000	0.000	0.000
Sep. 97	51	0.053	0.028	0.171	0.000	0.000	0.001
Oct. 97	26	0.052	0.010	0.166	0.001	0.000	0.002
Nov. 97	10	0.057	0.027	0.073	0.002	0.001	0.002
Dec. 97	0	0.000	0.000	0.000	0.002	0.002	0.002
Jan. 98	15	0.089	0.075	0.104	0.002	0.002	0.002
All year	349	1.087	0.539	1.814			
Annual[b]	349	1.392	0.073	2.783	0.001	0.000	0.003

[a] Time spent in cave per month (tour guide with more working hours accumulated).
[b] Using annual mean of radon level of 3562 Bq m^{-3}.

very important to have a substantial record of ^{222}Rn levels in caves to obtain a consistent record of radon variation over time, in order to know the whole range of values. Sporadic records can only reflect specific situations and therefore not necessarily the actual conditions.

Table 4
WLM calculated for tour guides and visitors to the cave using $F = 1.0$

Month	Tour guide				Visitor (20 min in cave)		
	Time[a]	Med. WLM	Min. WLM	Max. WLM	Med. WLM	Min. WLM	Max. WLM
Feb. 97	36	0.345	0.225	0.387	0.003	0.002	0.004
Mar. 97	38	0.348	0.136	0.430	0.003	0.001	0.004
Apr. 97	27	0.203	0.125	0.236	0.002	0.002	0.003
May 97	4	0.020	0.003	0.037	0.002	0.000	0.003
Jun.97	22	0.072	0.007	0.179	0.001	0.000	0.003
Jul. 97	54	0.145	0.034	0.460	0.001	0.000	0.003
Aug. 97	66	0.060	0.038	0.129	0.000	0.000	0.001
Sep. 97	51	0.076	0.041	0.245	0.000	0.000	0.002
Oct. 97	26	0.074	0.015	0.237	0.001	0.000	0.003
Nov. 97	10	0.081	0.039	0.105	0.003	0.001	0.003
Dec. 97	0	0.000	0.000	0.000	0.003	0.003	0.003
Jan. 98	15	0.128	0.108	0.148	0.003	0.002	0.003
All year	349	1.553	0.769	2.592			
Annual[b]	349	1.989	0.104	3.976	0.002	0.000	0.004

[a] Time spent in cave per month (tour guide with more working hours accumulated).
[b] Using annual mean of radon level of 3562 Bq m^{-3}.

In order to determine annual effective dose in mSv we used DCF of 5 mSv/WLM recommended by ICRP-65, 6 mSv/WLM (Madden et al., 1994; used by Duffy et al., 1996 in caves of Ireland), 8 mSv/WLM (median value proposal by Porstendörfer, 2002 in home and workplaces with "normal" and high particle concentration in aerosol conditions) and 10 mSv/WLM (NRPB, 1992). All values have also been determined for the three scenarios related to variations in F. Results are displayed in Table 5. Again, because of the substantial range of variation of radon concentration during a month inside the cave, annual dose varies between quite extreme ranges. In any case using average values, the upper limit (20 mSv yr^{-1}) recommended by ICRP-65 (ICRP, 1994) and European Normative (EC, 1990) is never surpassed.

Applying the DCF recommended by ICRP-65, the values only reach the limit in the worst case scenario: $F=1$ and using annual average of maximum levels of radon concentration. Using highest DCF (6 mSv/WLM or 8 mSv/WLM), the values surpass the limits in the same situation, but only if for calculations $F=1$ and annual accumulation of monthly maximum levels area used. A most realistic situation is defined using annual accumulated average values and $F<1.0$. In any case the effective dose exceeds the international recommendations.

Table 5
Annual effective dose received by tour guides and visitors to the cave using different DCF and equilibrium factor values

DCF	F	Annual dose[a]	Tour guide dose (mSv)			Visitor dose (mSv)		
			Med.	Min.	Max.	Med.	Min.	Max.
5 mSv/WL	0.5	1	3.9	1.9	6.5	–	–	–
		2	5.0	0.3	9.9	0.005	0.0	0.01
	0.7	1	5.4	2.7	9.1	–	–	–
		2	7.0	0.4	13.9	0.005	0.0	0.015
	1.0	1	7.8	3.8	13.0	–	–	–
		2	9.9	0.5	19.9	0.01	0.0	0.02
6 mSv/WL	0.5	1	4.7	2.3	7.8	–	–	–
		2	6.0	0.3	11.9	0.006	0.0	0.012
	0.7	1	6.5	3.2	10.9	–	–	–
		2	8.4	0.4	16.7	0.006	0.0	0.018
	1.0	1	9.3	4.6	15.6	–	–	–
		2	11.9	0.6	23.9	0.012	0.0	0.024
8 mSv/WL	0.5	1	6.2	3.1	10.4	–	–	–
		2	8.0	0.4	15.9	0.008	0.0	0.016
	0.7	1	8.7	4.3	14.5	–	–	–
		2	11.1	0.6	22.3	0.008	0.0	0.024
	1.0	1	12.4	6.2	20.7	–	–	–
		2	15.9	0.8	31.8	0.016	0.0	0.032
10 mSv/WL	0.5	1	7.8	3.9	13.0	–	–	–
		2	10.0	0.5	19.9	0.010	0.000	0.020
	0.7	1	10.9	5.4	18.1	–	–	–
		2	13.9	0.7	27.8	0.010	0.000	0.030
	1.0	1	15.5	7.7	25.9	–	–	–
		2	19.9	1.0	39.8	0.020	0.000	0.040

[a] 1, using $\sum$ monthly mean; 2, using annual mean.

In any of the above scenarios, visitors to the cave receive the maximum recommended annual dose (1 mSv yr^{-1}).

Since the main purpose of this study was to calculate the levels of radon that affect tour guides in Altamira cave (as users that spend more time in the cave) a useful approach is to calculate the maximum time that a tour guide will spend in the cave so as not to surpass the annual dose recommended by ICRP-65 and European Authorities. Table 6 shows suggested monthly times that tour guides will stay inside the cave in order to keep dose levels below 4 WLM per year, which is the maximum annual level, recommended using a DCF of 5 mSv/WLM. Monthly time was calculated using 11 working months (one holiday month), so 0.36 WLM per month was used as upper radon level limit not to be exceeded.

With the automatic radon monitoring system, the radon level is recorded every hour and the time spent inside the cave during this interval is also recorded. Thus, time remaining to reach the annual recommended 4 WLM (or 20 mSv using a DCF of 5 mSv/WLM) could be automatically updated by the use of a simple spreadsheet, as explained in Table 7.

4. Conclusions

Only a continuous short-term monitoring system can register the entire variation of radon concentration inside a cave over long periods. In the Altamira Cave the radon levels monitored inside the Polychromes Hall vary between a minimum of 186 Bq m^{-3} and a maximum of 7120 Bq m^{-3}, with an annual average of 3562 Bq m^{-3}.

The annual effective dose to tour guides varies between an average of 3.9 mSv and 12.4 mSv depending on the F and DCF values used to calculate it. Nevertheless, values are lower than the levels recommended by the ICRP and European

Table 6
Assessment of maximum time (h) allowed to guides inside cave not to surpass 4 WLM yr^{-1}

Month	$F=0.5$			$F=0.7$			$F=1.0$		
	t_{med}	t_{max}	t_{min}	t_{med}	t_{max}	t_{min}	t_{med}	t_{max}	t_{min}
Feb.	75	115	67	54	82	48	38	58	34
Mar.	79	202	64	56	144	45	39	101	32
Apr.	96	156	82	68	111	59	48	78	41
May	143	1006	78	102	719	56	72	503	39
Jun.	221	2435	89	158	1739	63	110	1217	44
Jul.	267	1135	84	191	811	60	134	568	42
Aug.	789	1251	368	563	894	263	394	626	184
Sep.	482	904	150	344	646	107	241	452	75
Oct.	252	1283	79	180	916	56	126	641	39
Nov.	89	184	69	64	132	49	45	92	34
Dec.	81	93	72	58	67	51	40	47	36
Jan.	85	100	73	60	72	52	42	50	36
All year	2658	8865	1275	1898	6332	911	1329	4432	638
Annual	1413	27054	707	1009	19324	505	706	13527	353

Table 7
Example of spreadsheet to calculate accumulated WLM after each visit in order not to surpass 4 WLM yr^{-1}

Time inside cave per visit (h)	^{222}Rn level in cave during a visit (Bq m^{-3})	Proportional WLM per visit	Accumulated WLM
t_1	R_1	WLM_1	WLM_1
t_2	R_2	WLM_2	WLM_1+WLM_2
…	…	…	
t_n	R_n	WLM_n	$WLM_1+WLM_2+\ldots+WLM_n$

Where n is total number of visits to accumulate 4 WLM.

authorities. In all the cases, visitors receive during a tour level much less than the maximum annual dose recommended to the public.

A strict record of the duration of a stay (with dates and hours) of stay inside the cave by each person is essential in order to calculate effective dose of radon affecting tour guides and other workers. This, in conjunction with a precise record of radon concentration inside the cave, is an accurate way to calculate dose of radon accumulated in each visit without the use of a dosimeter.

The use of the annual average of radon concentration in cave may not represent a realistic situation, and can lead to the overestimation (in the case of mean and maximum values) or underestimation (in the case of minimum values) of the real data. When monthly, weekly or even hourly data are available, monthly effective dose could be calculated in order to monitor the annual dose that a tour guide receives during the whole year (by the use of a simple spreadsheet). If it is possible determine the effective dose that received a tour guide during each visit, will be more effective determine the time (in hours) that remains to reach the annual dose recommended.

As several authors have shown (Solomon, 2001; Porstendörfer, 2002) the DCF recommended by the ICRP-65 will lead to doses being underestimated and a higher DCF has therefore been proposed. In the light of using different DCF values from those suggested by the ICRP, studies about the effective dose of radon that workers may receive should perhaps be re-assessed.

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References

Denman, A.R., Parkinson, S., 1996. Estimates of radiation dose to National Health Service workers in Northamptonshire from raised radon levels: Short communication. British Journal of Radiology 69, 72–75.

Dueñas, C., Fernández, M.C., Cañete, S., Carretero, J., Liger, E., 1999. ^{222}Rn concentrations, natural flow rate and the radiation exposure levels in the Nerja Cave. Atmospheric Environment 33 (3), 501–510.

Duffy, J.T., Madden, J.S., Mackin, G.M., McGarry, A.T., Colgan, P.A., 1996. A reconnaissance survey of radon in show caves in Ireland. Environment International 22 (1), 415–423.

European Communities (EC), 1990. Commission Recommendation 90/143/EUROATOM of 21 February 1990 on the protection of the public against indoor exposure to radon. Off. J. L-80, 26–28.

Fernández, J., Quindós, L.S., Soto, J., Villar, E., 1984. Radiation exposure levels in Altamira Cave. Health Physics 46 (2), 445–447.

Fernández, J., Gutierrez, I., Quindós, L.S., Soto, J., Villar, E., 1986. Natural ventilation of the Painting Room in the Altamira cave. Nature 321, 586–588.

Furuta, S., Ito, K., Ishimori, Y., 2002. Measurements of radon around closed uranium mines. Journal of Environmental Radioactivity 62 (1), 97–114.

Gillmore, G.K., Sperrin, M., Phillips, P., Denman, A., 2000. Radon hazards. Geology and exposure of cave users: a case study and some theoretical perspectives. Ecotoxicology and Environmental Safety 46 (3), 279–288.

Gillmore, G.K., Phillips, P., Denman, A., Sperrin, M., Pearce, G., 2001. Radon levels in abandoned metalliferous mines, Devon, Southwest England. Ecotoxicology and Environmental Safety 49, 281–292.

Gillmore, G.K., Phillips, P.S., Denman, A.R., Gilbertson, D.D., 2002. Radon in the Creswell Crags Permian limestone caves. Journal of Environmental Radioactivity 62 (2), 165–179.

Hakl, J., Hunyadi, I., Csige, I., Géczy, G., Lénárt, L., Várhegyi, A., 1997. Radon transport phenomena studied in Karst caves: international experiences on radon levels and exposures. Radiation Measurements 28 (1–6), 675–684.

Hoyos, M., 1993. Procesos de alteración de soporte y pintura en diferentes cuevas con arte rupestre del Norte de España. In: Fortea, J. (Ed.), La Conservación y Protección del Arte Rupestre Paleolítico. Ministerio de Cultura, Oviedo, pp. 77–85.

Hyland, R., Gunn, J., 1994. International comparison of cave radon concentrations identifying the potential alpha radiation risks to British cave users. Health Physics 67, 176–179.

International Commission on Radiation Protection, 1986. Radiation Protection of Workers in Mines. ICRP Publication, 471986. Pergamon, Oxford.

International Commission on Radiation Protection, 1994. Protection Against Radon-222 at Home and at Work. ICRP Publication, 651994. Pergamon, Oxford.

Kies, A., Massen, F., Feider, M., 1997. Measuring radon in underground locations. In: Virk, H.S. (Ed.), Rare Gas Geochemistry. Guru Nanak Dev University, Amritsar, pp. 1–8.

Madden, J.S., 1997. Personal monitoring of tour guides in Irish show caves. European Conference on Protection against Radon at Home and at Work, Prague, pp. 123–128.

Madden, J.S., Duffy, J.T., Mackin, G.A., Colgan, P.A., McGarry, A.T., 1994. Radon in dwellings in selected areas of Ireland. Radiological Protection Institute of Ireland Report 94/3, Dublin.

National Radiological Protection Board (NRPB), 1992. Radon affected areas, Derbyshire, Northamptonshire and Somerset. Documents of the NRPB 3 (4).

Porstendörfer, J., 2002. Influence of physical parameters on doses from radon exposures. International Congress Series 1225, 149–160.

Qureshi, A.A., Kakar, D.M., Akram, M., Khattak, N.U., Tufail, M., Mehmood, K., Jamil, K., Khan, H.A., 2000. Radon concentrations in coal mines of Baluchistan, Pakistan. Journal of Environmental Radioactivity 48 (2), 203–209.

Real Decreto 783, 2001. Reglamento sobre protección sanitaria contra radiaciones ionizantes. Boletín Oficial del Estado, 178.

Sánchez-Moral, S., Soler, V., Cañaveras, J.C., Sanz-Rubio, E., Van Grieken, R., Gysels, K., 1999. Inorganic deterioration affecting the Altamira Cave, N Spain: quantitative approach to wall-corrosion (solutional etching) processes induced by visitors. The Science of the Total Environment 243–244, 67–84.

Solomon, S.B., 2001. Field tests of a radon progeny sampler for the determination of effective dose. The Science of the Total Environment 272 (1–3), 303–313.

Solomon, S.B., Cooper, M.B., O'Brien, R.S., Wilkinson, L., 1992. Radon exposure in a Limestone Cave. Radiation Protection Dosimetry 45 (1/4), 171–174.

Sperrin, M., Denman, T., Phillips, P., 2000. Estimating the dose from radon to recreational cave users in the Mendips, UK. Journal of Environmental Radioactivity 49, 235–240.

Valladas, H., Cachier, H., Maurice, P., Bernardo de Quiros, F., Clottes, J., Cabrera Valdés, V., Uzquiamo, P., Arnold, M., 1992. Direct radiocarbon dates for prehistoric paintings at the Altamira, El Castillo and Niaux caves. Nature 357, 68–70.

Wrixon, A.D., Green, B.M.R., Lomas, P.R., Miles, J.C.H., Cliff, K.D., Francis, E.A., Driscoll, C.M.H., James, A.C., O'Riordan, M.C., 1988. Natural Radiation Exposure in UK Dwellings. National Radiological Protection Board Report R190, NRPB, Chilton, UK.

Yamada, Y., 2003. Radon exposure and its health effects. J. Health Sci. 49 (6), 417–422.