ASSESSMENT OF HEALTH RISKS TO SKIN AND LUNG OF ELEVATED RADON LEVELS IN ABANDONED MINES

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***Abstract*—Radon, together with its progeny, is present in high levels in some underground sites. Radon is known to increase the risk of lung cancer, while increased levels of radon decay products on the skin surface have been implicated in skin cancer induction and at sufficient levels might cause deterministic effects such as erythema. Although radon levels in working mines are controlled, radon in abandoned mines can reach very high levels, which would result in an occupant exceeding recommended annual exposure limits in less than 2 h in some mines. The relative importance of dose limits for the lung, skin cancer, and deterministic effects is discussed in the light of practical experience.**

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Key words: radon; skin dose; lungs, human; health effects

INTRODUCTION

RADON IS a naturally occurring radioactive gas that is created by decay of uranium, which itself has a variable distribution in soil and rock. Radon gas can concentrate in buildings where raised levels are now considered a human health hazard. However, the health risks of radon were first established in miners due to the increased numbers of lung cancers in mines with raised levels of radon (ICRP 1994; Morrison et al. 1998).

It should be noted that most of the dose received by the lungs is not from radon itself, but from two of its decay products, ^{218}Po and ^{214}Po, which are both radioactive, and, like ^{222}Rn, emit alpha particles. In practice, radon never reaches equilibrium with its progeny because of ventilation, plate out of the progeny, and other processes, as described by Porstendörfer (1984). In buildings, the ratio between radon progeny and radon itself is in the range 0.4 to 0.6, and this ratio, known as the equilibrium factor (F), as well as the radon level itself, is one of the important factors determining the health risk to occupants.

Radon progeny can plate out on to occupants' skin, and it has been shown that the alpha particles emitted by both polonium isotopes, when on the skin, can reach the basal cells of the epidermis, which lie between 20 and 100 μm deep (ICRP 1991). The effects of ionizing radiations on the skin have been studied and at high doses can cause erythema and hair loss, and at lower doses an increased risk of skin cancer (NRPB 1997). This would suggest that radon may be responsible for a small percentage of the non-melanoma skin cancers occurring in the UK (Eatough and Henshaw 1995).

In Cornwall and Devon, extensive deposits of tin and copper ore lie close to the roof of a granite batholith, which cuts across a well-folded succession of Devonian and Carboniferous slates, shales, sandstones, limestones, and volcanic rocks. This tin is often closely associated with uranium ores (Strong et al. 1975), and hence many of these old workings have very high radon levels.

The mining of tin and other metals in Cornwall and Devon has been carried out since pre-Christian times (Smith 1863; Wolfe 1970). Vein minerals such as tin were mainly worked by sub-level stopping (O'Riordan et al. 1981). The workings examined in this study are mostly simple horizontal tunnels (known as adits) cut into the hillside, but it is not uncommon for these abandoned mines to have quite extensive galleries.

Where elevated radon levels have been found in working mines, these can be reduced by positive ventilation, sealing off old workings, and controlling mine water (Arthur 2000). Indeed, it is a requirement of the Ionising Radiations Regulations (IRR 1999) that employers do this in the UK to reduce average radon levels below 400 Bq m^{-3}, or by restricting access.

However, at the end of their working life, mines are often abandoned and the added ventilation removed, so that radon levels rise. In some abandoned mines, levels as

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high as 7 × 10^6 Bq m^{-3} have been recorded (Gillmore et al. 2001). Access may be unrestricted, and groups interested in industrial archeology, for example, may wish to investigate such mines. This paper assesses the radon levels in abandoned mines and considers the lung and skin dose received by visitors.

METHODS

Locations

Mine A. Mine A is found in the Southern Dartmoor, Devon region of the UK, and has a west-facing entranceway. Dines (1956) noted that the granite outcrop in this area also has several "unimportant" tin mines. The mined lodes consist almost invariably of quartz-tourmaline veins, often thin, with tourmalinized or pink stained wall rock, generally hard, but soft and decomposed in parts. The lodes carry cassiterite (tin ore), usually in comparatively coarse grains. Lodes were worked at the surface and occasionally at depth. The deepest workings known did not exceed 73 m vertical depth. The recorded output from this area, although incomplete, does suggest that a little over 300 tons of "black tin" were exploited. Some of the "black tin" was also extracted from alluvial deposits in the area rather than from the lodes themselves (Dines 1956).

Mine A has three lodes; one to the north of ancient prehistoric barrows, and two to the south, all lodes coursing north of east (Dines 1956). Mine A has a low stone lined portal 1 m high by 75 cm wide with a barrel-shaped passageway inside. The roof and walls are made of compacted soil with pebbles of granite near the entranceway. A solid granite passageway continues into the hill. The deepest point measured for radon levels was at 180 m horizontal depth. The floor material is of crushed granite fragments rather than the usual mud found in such mines.

Mine A has fairly limited air circulation due to the small entranceway. However, the dominant wind direction would be from the west and south-west in this region of the UK, although wind directions at the surface are subject to variations as a result of topography and the location of depression centers (Wheeler and Mayes 1997). With a west-facing entranceway air may be blowing into the mine for most of the year. This may reduce radon levels and equilibrium factors in the shallower parts of the mine.

Mine B. Mine B, also found in Southern Dartmoor, is of similar construction to Mine A with an entrance way that is approximately 1 m high and 60 cm wide, but is only 8 m horizontal depth. This adit contained particularly coarse porphyritic granite, with the tin being found in tourmaline rich veins a few centimeters thick.

Mine B has a narrow entranceway that limits air circulation; however, the shallow depth of the adit also means that the radon levels and equilibrium factors inside the old workings will be more affected by external air. Gillmore et al. (2002) highlights that radon levels in caves are affected by outside air to a horizontal depth of about 20 m from the entrance.

Mine C. Mine C is located near St. Austell in Cornwall. This mine was a trial made in 1922 in search of a uranium lode (Dines 1956). Tin lodes were noted nearby by Dines (1956). Like Mines A and B the entranceway for Mine C was fairly limited, although it is easier to walk into the mine standing. This adit was driven for approximately 245 m east-south-east, and connected at 75 m from the entrance with a vertical shaft 41 m deep. Some 92 m from the entrance, drives follow narrow quartz veins that were unfortunately barren of uranium ore. Some 216 m from the entrance, the adit passes through a 5.5 m wide elvan dyke. (A local mining term meaning a dyke of granite, microgranite, or quartz porphyry. A quartz porphyry is a medium grained rock containing phenocrysts of quartz; otherwise known as porphyritic microgranite.) From here radioactive water enters the workings (Dines 1956).

Measurements

Each mine was studied by measuring both radon and progeny levels. Radon levels were assessed using either an Alphaguard or a Durridge RAD7 meter, both recently calibrated, which measured radon levels over a 10-min sampling period. The Alphaguard detects radon gas using an open-ended ionization chamber into which radon gas can passively diffuse. Radon progeny are prevented from entering the chamber by an aerosol filter. The RAD7 actively pumps air into a measurement chamber through a drying agent and a 0.44 micron filter to remove progeny. Alpha particles emitted by radon are measured by a semi-conductor diode.

Some additional spot measurements were made using etched track detectors. The latter were exposed for between 20 min and 168 h, depending on the expected radon level, to ensure adequate counting statistics and to avoid saturation of the detectors.

Radon progeny levels were assessed using a working level meter. This meter draws air through a filter paper, which collects any progeny in the air. Alpha emissions from the progeny are counted by a solid state detector fixed directly above the filter paper.

The working level meter gives results in working levels, where 1 Working Level is defined as 1.3×10^5 MeV of potential alpha energy per liter of air. To compare the result with radon gas levels the measurement is multiplied by 3,740 to give the equivalent radon gas concentration if the progeny were in equilibrium with the gas. This is known as the equilibrium equivalent concentration (EEC). The ratio between the EEC and the radon gas level is the equilibrium factor (F).

In practice, F never reaches 1 (i.e., equilibrium), because of ventilation processes and plate out of progeny. In the built environment, F is around 0.4 to 0.6 (Knutson 1983), but in mines and caves it can be more variable. UNSCEAR (1988) suggests that for domestic environments F is typically 0.35. Snihs and Ehdwall (1976) measured the equilibrium factor in 37 working Swedish mines, and results ranged from 0.4 to 1.0, with an average value of 0.7. Initial investigation in fairly shallow parts of mines in Cornwall and Devon by Gillmore et al. (2001) suggested equilibrium factors in the range 0.17 to 0.4, although it was noted that F varied spatially and temporally quite considerably. Domański et al. (1979), in a study of deep and territorially large mines over a 2-y period, took over 300 measurements of radon concentration and concentration of potential alpha energy of radon progeny. They concluded that the best values of F for usual mine conditions and ventilation (their mines consisted of a copper mine and a lead-zinc mine) were between 0.2 and 0.3. Domański (1979) presented calculated values of approximately 0.09 to 0.65 in a study on correlating equilibrium factors and relative concentration of radon progeny in mine air. He concluded that in mine air F rarely goes above 0.7. Cavallo (2000) presented data from New Mexico uranium mines that suggest values of 0.05 to 0.27, the average being 0.17. These data were obtained from working mines that were well ventilated.

Dose assessments

The effective dose received by occupants was estimated using the relation that 1 mSv is received from a cumulative exposure of 126 kBq m^{-3} h, as derived by the National Radiological Protection Board (NRPB) (Wrixon et al. 1988), assuming F to be 0.5, and the relation that 10 mSv is equal to 1 Working Level Month (HSC 1988). The calculated dose was modified by the actual equilibrium factor.

Lung. The risk of lung cancer was estimated from the Working Level Meter reading using the latest NRPB estimate of risk to the general public of 3.5×10^{-4} lung cancers per Working Level Month (NRPB 1993), where one Working Level Month is the exposure resulting from 1 Working Level over 170 h. The recent BEIR VI report (1999) notes that while individual risk may vary due to age and smoking habits between individuals, their general population risk estimates are similar to previous estimates. It should be noted that the doses, estimated here, used the NRPB methodology noted above. ICRP (1994) uses a different methodology and using their method, which assumes an equilibrium factor of 0.4, the doses are around a factor of 2 lower, but the estimates of lung cancers are similar because lung cancer estimates are based on radon exposure rather than dose.

Skin. Eatough et al. (1999) used a novel etched track detector worn as a modified wrist watch to measure total alpha activity on the skin at low radon concentrations and found it to be 1.35 ± 0.8 Bq m^{-2} Bq^{-1} m^3 Equivalent Equilibrium Concentration (EEC). The detectors were worn by a number of volunteers living in radon affected areas who could have been exposed to elevated radon levels in the overground workplace and their homes.

Sevcova et al. (1978) measured the total alpha activity on the skin of underground uranium miners and found it to be 2.3 ± 0.7 kBq m^{-2} at 1,160 Bq m^{-3} EEC, which amounts to 2.0 ± 0.6 Bq m^{-2} Bq^{-1} m^3 EEC.

Both values are consistent within the experimental error, suggesting that any differences between working conditions of the two groups and differences between the radon levels have little effect on the deposition rate of progeny on the skin. Nevertheless, the value determined by Sevcova et al. (1978) was used in the following calculations as the conditions are closer to those in abandoned mines.

The critical cells in the skin are in the basal layer of the epidermis, and the emitted alpha particles must penetrate the outer layers to reach these cells. Eatough (1997) estimated that, for nuclides attached to the actual skin surface, the dose to the basal layer is around 0.5 μSv $decay^{-1}$ cm^2 for ^{218}Po, which emits a 6.0 MeV alpha particle, and 1 μSv $decay^{-1}$ cm^2 for ^{214}Po, with a 7.69 MeV alpha. Eatough et al. (1999) suggest, from their measurements, that the relative activity of ^{214}Po and ^{218}Po is about 50:50.

One uncertainty in the assessment of skin doses from radon progeny concerns the proportion of the nuclides that attach to the hairs on the skin rather than to the skin surface itself. The skin dose from those nuclides attached to hairs remains to be mathematically modeled, but the dose from such nuclides will be much less than those on the skin surface because the short range alpha particle passes through air and/or hair before reaching the skin. An initial approach is to assume all the nuclides are attached to the skin surface and none to hair, and this is used for the results below. This is unrealistic for most parts of the body and so will produce an upper limit for the dose estimation, which may be approximately valid for some parts of the skin, such as the face. The possibility of increased deposition on to hair should also be considered. It is difficult to produce a likely lower limit without modeling the hair attachment fraction, and the lower limit of dose would vary between individuals, depending on the degree of surface hair.

Finally, it should be noted that this analysis applies to uncovered skin and that clothing can greatly reduce, or eliminate, skin dose. In particular, alpha particles emitted from progeny deposited on the clothing rather than skin are unlikely to reach the basal layer.

RESULTS

The results of the various radon measurements in Mines A, B, and C are shown in Table 1. The estimated equilibrium factor for each mine is shown in Table 2. In each case the equilibrium factor is low, with Mine A showing some variation, with a lower value near the entrance.

These results can be used to derive effective and skin dose rates using the methods noted above. For example, Mine C has an EEC of 143,900 Bq m^{-3}. This gives a predicted total alpha activity on exposed skin of 28.8 Bq cm^{-2}. The skin activity in Mine C would therefore be 14.4 Bq cm^{-2} for each nuclide and the skin dose would be 21.6 μSv s^{-1} or 78 mSv h^{-1}. Calculated effective and skin dose rates for each mine are shown in Table 2.

DISCUSSION

The significance of the dose rates shown in Table 2 depends on the frequency and duration of visits, which is normally related to the ease of access to the mine.

In the UK, under the Ionising Radiation Regulations 1999 (IRR 1999), non-classified radiation workers are restricted to an effective dose of 6 mSv per annum, but the regulations also set a limit of 400 Bq m^{-3}, and these limits apply to working mines and show caves. However, the regulations do not apply to voluntary groups, such as those interested in industrial archaeology. To cover such visits to caves and mines, the NRPB (Dixon 1996) issued guidance suggesting that individual exposure be limited to 10^{6} Bq m^{-3} h.

Radiation damage to the skin was the first type of radiation health risk to be described (NRPB 1997). Transient erythema can occur after a few hours at x-ray doses over 2 Gy. Dry desquamation and transient epilation can also occur, but ICRP (1991) consider that moist desquamation that occurs at x-ray doses over 10 Gy to the basal cells is the reaction to be prevented. For chronic exposures, the limiting effect is dermal thinning, and the threshold for this is above 0.5 Gy for x rays. The occupational limit for skin, stated in the Ionising Radiations Regulations (IRR 1999), is 500 mSv per annum at the skin surface averaged over 1 cm^{2} for classified workers, and this has been established to limit the possibility of these deterministic effects. Baum (2001) argues that a unified dose limit of 500 mSv at a depth of 70 μm averaged over 10 cm^{2} is more appropriate.

Most of the work on skin damage described by ICRP (1991) is from x rays, a low linear energy transfer (LET) radiation. However, the alpha particles given off by radon and its progeny are high LET radiation. Such radiation is more effective in creating biological damage, and therefore when considering radiation protection from high LET radiation, a radiation weighting factor of 20, known as the quality factor, is used to convert to Sieverts. However, the relative response of high and low LET radiation, known as relative biological effectiveness (RBE), varies depending on the cells or tissues exposed and on the type of injury studied.

Erythema caused by alpha particles emitted by ^{210}Po has been reported in the literature. Witten et al. (1957) irradiated skin of volunteers using plaques of ^{210}Po covered by gold foil and demonstrated that transient erythema appeared within 2 to 8 h above a threshold of 200 Gy to the skin surface. The higher the dose, the prompter the appearance of erythema. The alpha particle emitted by ^{210}Po has an energy of 5.3 MeV, lower than those of ^{214}Po and ^{218}Po, and this, combined with the

Table 1. Radon gas and progeny levels in each mine.

	Date	Position	Radon (kBq m^{-3})	Progeny (WL)
Mine A	8 April	Near entrance	400	14
	8 April	Just before crawl	570	27
	8 April	Just after crawl	420	
	8 April	Left end chamber	400	
	8 April	Furthest point in	440	
Mine B	25 June	Furthest point in	60	
	11 July	Furthest point in		3
Mine C	17 June	End of passage	700	39

Table 2. Equilibrium factors and dose rates in each mine.

Mine	Equilibrium factor	Effective dose in mSv h^{-1}	Equivalent dose to skin in mSv h^{-1}
A—near entrance	0.13	0.8	27
A—just before crawl	0.17	1.6	53
B	0.18	0.17	5.8
C	0.21	2.3	78

presence of the gold foil, implies that only a small proportion of the alpha particle surface dose reached the basal layer in Witten's experiment. It would be anticipated that alpha particles from ^{214}Po and ^{218}Po would be much more efficient at causing erythema, but in the absence of detailed knowledge of the depth of the target cells, extrapolation of the results of Witten et al. to radon-related alpha particle damage would be difficult.

Eatough et al. (1999) used the usual radiation weighting factor of 20 in deriving the dose to the basal layer quoted above. However, Eatough and Henshaw (1995), reviewing a series of animal and cell experiments, suggest that an RBE of 5 may be more appropriate for skin cancer induction.

Table 3 indicates the time spent in each mine to reach the respective limits for effective dose and skin dose. It can be seen from the Table that the NRPB guideline of 10^6 Bq m^{-3} h is the most restrictive limit for the mines studied and would ensure that the effective dose received is limited to around 2 to 3 mSv and that no deterministic effects to the skin would occur. However, this limit is for radon gas, not progeny, and so in stagnant caves with high equilibrium factors, the NRPB guidelines may not ensure that whole body effective dose is below 6 mSv y^{-1}. Przylibski (2001) studied an extensive former arsenic and gold mine in Poland, and found that F ranged from 0.2 to 0.9, but that sections with higher F were inaccessible to the casual visitor. This is also likely to be the case in mines in the UK.

The apparently long time to reach an erythemal skin dose contrasts with some observations, where visitors to another mine allegedly reported transient skin erythema after spending 20 min in a mine with a radon level of 6 × 10^6 Bq m^{-3}. Skin dose in this case would have been around 200 mSv and, therefore, below the threshold for acute effects. This occurred on an occasion of high humidity, with water flowing through the mine and mist in the air. Pertinent questions include whether the equilibrium factor was raised due to the misty conditions because of the high attached fraction on the water vapor, and whether the passage of people through the mine disturbed the radon and decay products levels transiently, perhaps by releasing radon from the water. In addition, the presence of water droplets in the mist may affect the deposition rate on to the skin surface. Paulo et al. (2001) have observed similar increased plate-out in the laboratory when track etched detectors of different shapes and sizes are introduced; while Leonard (2003) has observed increased deposition at high radon levels. This can only be assessed by real-time personal monitoring of decay products.

In addition to the deterministic effects on the skin, there is evidence that radiation can increase the incidence of skin cancer, and the NRPB (1997) estimate that the lifetime risk of non-melanoma skin cancer incidence is 2.3 × 10^{-2} Sv^{-1}. This risk estimate, also used by ICRP (1991) and Eatough and Henshaw (1995), has been estimated for the face and neck and assumes that other areas of skin are covered or (for the hands) have too thick a dermal layer. These assumptions mirror the findings of the various studies of cancer induction reviewed by NRPB (1997). However, since non-melanoma skin cancer is rarely fatal, the lifetime mortality risk of non-melanoma skin cancer is much lower at 3.2 × 10^{-4} Sv^{-1}. Darby et al. (1995) have conducted a meta-analysis of 11 studies of underground miners and concluded that there was no substantive evidence of increased mortality of cancers other than lung. However, Sevcova et al. (1978, 1984) and Sevc et al. (1988) observed an increase in incidence of skin cancer in uranium miners, and Sevc et al. (1988) estimated this risk to be 1.0 × 10^{-4} Sv^{-1} y^{-1}.

Table 4 summarizes the increased lifetime risk of skin cancer resulting for a 1-h exposure in each mine.

Some groups, interested in industrial archaeology, visit such mines. Responsible groups, having discovered raised radon levels, adopt operational precautions to reduce the impact of raised radon levels. In mines with very high radon levels, a mask with filter and an all-in-one suit that covers all skin surfaces are worn. This

Table 3. Time in hours to reach exposure limits.

Mine	Effective dose of 6 mSv (IRR99)	Equivalent dose to skin of 500 mSv (IRR99)	Skin erythema (2 Sv)	NRPB guidelines (1 MBq m^{-3} h)
A—near entrance	8	19	74	2.5
A—just before crawl	4	9	38	1.8
B	35	86	345	17
C	2.6	6.4	26	1.4

Table 4. Lifetime risk of skin cancer following 1-h exposure.

Mine	Lifetime risk
A—near entrance	4×10^{-5}
A—just before crawl	8×10^{-5}
B	0.8×10^{-5}
C	11×10^{-5}

will eliminate all dose except that from radon gas itself, which will reach the lungs. At lower levels, time spent in the mine is limited by working to the NRPB limit. However, these precautions are voluntary, and there is no guarantee that enthusiastic amateurs will comply with them.

In each case, the mines are sited on public land, with unrestricted access. This raises questions of whether, and how, access can be restricted so that exposures are not excessive.

CONCLUSION

The radiation dose received from radon exposure in abandoned mines in the West Country of the UK can be considerable. In some mines, the radon level can be so high that acute effects such as skin erythema might be observed for prolonged exposure. Anecdotal evidence suggests that this may occur at apparently lower doses than expected, and this should be investigated, particularly to see whether mist present in high humidity mines, or disturbance of mine water, increases the progeny plating out on skin.

The results indicate that if visitors ensure that their radon exposure is below the NRPB guideline of 10^6 Bq m^{-3} h in 1 y, then the skin dose and effective dose will both be below the annual limits for UK radiation workers and below the levels at which any acute skin effects will occur.

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