Chapter 3

Radon Monitoring in the Environment

Abd Elmoniem Ahmed Elzain

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.69902

Abstract

Radon is a natural radioactive gas used to estimate the radioactive hazard in the environment. Radon (222Rn), which is one of the daughters of uranium (238U), represents the most essential isotope, with a half-life of 3.825 days. The associated health risks due to inhalation and ingestion of radon and its progeny when present in enhanced levels in an indoor environment like a human dwelling have been documented. In this chapter, we have discussed the sources and techniques besides the methods used for measuring radon gas in the environment including soil, water, building materials, etc., which are well documented. A wide range of techniques for the detection and quantification of radon has been developed over the last few years. There is no single technique that can meet all the requirements of the different types of the radon measurements. Finally, we have mentioned the most essential information effecting the radon monitoring in the environment and the methods of measuring and controlling the concentration values throughout the environment; we have also mentioned the effect of radon on the inhabitants through the estimation of the effective dose rates and lung cancer risk due to radon gas when its values exceed the action level values.

Keywords: indoor radon, radioactivity dose rate, sources of radon, relative risk of lung cancer, passive and active techniques

1. Introduction

Radon is a radioactive noble gas that does not chemically react with other elements. However, it can change the physical properties of the surrounding medium. Radon (^{222}Rn), which is one of the daughters of uranium (^{238}U), represents the most essential isotope, with a half-life of 3.825 days. Its half-life allows it to migrate long enough to travel long distances and accumulate into the indoor environment. Radon (^{222}Rn) and its short-lived decay products

(^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) in dwellings are recognized as the main sources of public exposure from the natural radioactivity, contributing to nearly 50% of the global mean effective dose to the public [1]. The interest in studying radon behaviour is mainly due to the fact that it can accumulate indoors and in case of entering into the body can have serious damage to the human respiratory and gastrointestinal systems. The human respiratory tract due to radiation, radon and its daughter nucleus after entering the body is exposed to the most damage, producing an increased risk to the population. Therefore, after smoking, the second factor of lung cancer is radon [2]. The associated health risks due to inhalation and ingestion of radon and its progeny when present in enhanced levels in an indoor environment, water and soils surrounding a human dwelling have been well documented [3–7]. The radon concentration is usually depending on many parameters: including the radium content in the soil, meteorological parameters and the radon emanating from various soils and rocks [8, 9].

The radon concentration in the ground depends on the radium content of the soil and the emanation power of soils and rocks [10]. Among many factors affecting radon exhalation, one of the most important is radium content of the bedrock or soil. However, radon exposure shows an extreme variation from location to location and depends primarily on the exhalation rate of radon from the soil. It was recorded that radon exhalation rate studies are important for understanding the relative contribution of the material to the total radon concentration found inside the dwellings [11–13]. Radon and its daughters are emitted from building materials; one source of radon in houses is the building materials. The radon exhalation rate studies for building material samples are important for understanding the relative contribution of the material to the total radon concentration found inside the dwellings. It was shown that the radon exhalation rate decreases with the building age [14–16].

Radon contained in water is to some extent transferred into room air as a result of agitation or heating [17, 18]. UNSCEAR 2000 reported that radon concentration as a rule is much lower in surface water than in groundwater; radon concentrations in groundwater are expected to be 40 Bq L^{-1}; the mean dose from radon in water from inhalation was 0.025 mSv y^{-1} and 0.002 mSv when swallowed [1]. According to the WHO, the mean of the radon concentrations in tap water from surface waters equals 0.4 Bq L^{-1} and in well water is 20 Bq L^{-1} [19]. The release of radon from water to air depends upon circumstance in which the water is used, as the degassed fraction increases considerably with temperature. A recent report of large radon concentration in drinking water has added a new element of deep concern to the problem of environmental health hazards [20–22]. Measurements of radon concentration in water have mostly been undertaken in regions where high levels were suspected. It was tentatively estimated in the UNSCEAR 1982 Report (Annex D, Paragraph 163) that between 1 and 10% of the world's population consumes water containing radon concentrations of the order of 100 Bq L^{-1} or higher, drawn from relatively deep wells. For the remainder, who consume water from aquifers of surface sources, the weighted world average concentration is probably less than 1 kBq m^{-3} [23]. The International Commission for Radiological Protection has suggested that areas where 1% or more of the building have indoor radon concentration 10 times higher than that of national average should be considered as "radon prone" areas. It is

also recommended that radon concentration value ranges 500–1500 and 200–600 Bq m^{-3} for work places and dwellings, respectively; those concentrations do not pose a significant risk for workers [2]. Therefore, it is desirable not only to measure the radon but also to find out the sources of radon especially in the houses [4]. Other sources such as natural gas also contribute towards radon activity in dwellings, which depends upon their origin and the rate of consumption.

2. Sources of radon

2.1. Indoor sources

The studies of indoor radon levels have been conducted with long- and short-term methods in order to assess the indoor radon problems [24–26]. Indoor radon is influenced by many sources, such as soil, building materials, water and natural gas. A correct calibration procedure is paramount for good accuracy of results. Hence, precalibrated techniques either passive or active were used to study indoor radon-222 concentrations. These techniques were used in monitoring radon concentration through the entire environment [27, 28]. For such techniques as the solid state nuclear track detectors (SSNTDs), track density could be determined and then converted into activity concentration C_{Rn} (Bq m^{-3}) using the following equation [29]:

$$C_{Rn} = \frac{\rho_{Rn}}{K_{Rn}T} \tag{1}$$

where ρ_{Rn} is the track density (tracks per cm^2), K_{Rn} is the calibration constant, which must be previously determined in tracks cm^{-2} h^{-1} per (Bq m^{-3}) and t is the exposure time.

2.2. Outdoor sources

The quantity of radon in the earth is very small and amounts to about 4×10^{-7}% by weight. The main source of radon outdoors is the radium in the earth crust; at least 80% of the radon emitted into the atmosphere comes from the top few metres of the ground [30, 31]. The concentration of uranium and radium in the ground varies with types of rocks and minerals. The world average concentration for soils is about 24 Bq kg^{-1} for uranium-238. The concentration of radium in rocks and soil is often (but not always) the same as that of uranium.

2.3. Soil sources

2.3.1. Emanation

The emanation of radon atoms from a material is the process by which the radon atoms escape from a quantity of the material. The mechanisms of radon release from rock, soil and other materials are not very well understood and are probably not the same. It was reported that the emanation rate of radon is influenced by the condition of soil and its porosity, moisture content, temperature and atmospheric pressure [23, 32]. If the moisture content is very low, then the radon release is decreased by the effect of re-adsorption of the radon atoms on

surfaces in the pores. On the other hand, if the moisture content increases slightly, the radon release increases up to a certain moisture content, above which the release of radon decreased again owing to the decreasing diffusion rate in water-filled pores [33]. It was found that the emanation of radon from soil depends not only on the ^{238}U and ^{226}Ra concentration but also on the nature of the host mineralogy and the permeability of the host rock and the soil. It was found that the effect of paint, in general, is to reduce the radon emanation from the brick surfaces, which increases the radon concentration inside the brick. The emanation of radon increases from the unpainted area of the brick due to the increase of radon concentration inside it. It was also found that the radon emanation increases from brick covered with gypsum and plaster; therefore, the internal finish can increase the radon concentration inside houses [34].

2.3.2. Diffusion

Diffusion is identified as the principal method by which radon is transferred into and out of the basement modules and appears to be relatively independent of insulating materials and vapour retarder. It was found that the variability of radon and correlations with differential pressure gradients may be related to air current in block walls and soil that interrupted radon diffusion inward. Once radon has entered the air or water surrounding the emanating radium-bearing particle, it is transported by diffusion, earth mechanical and convective flow, percolating of rainwater and flow of groundwater. It was shown that there is insufficient evidence to accept the pressure-driven mechanism as the dominant mechanism of radon infiltration in homes, and thermo-diffusion gas flow in clay and concrete can greatly exceed the pressure-driven flow [35].

2.3.3. Flux from the soil

The radon emanation and exhalation rates in soil vary from place to another due to differences in radium concentration and soil parameters, such as moisture content, porosity, permeability and grain size. The moisture content of the soil is defined as the mass of water in the soil expressed as a fraction of the dry weight of the solids forming the soil matrix [36, 37]:

$$\% \text{ moisture content} = \frac{\text{mass of soil water}}{\text{mass of dry soil solids}} \times 100 \tag{2}$$

$$\% \text{ moisture content} = \frac{W_1 - W_2}{W_2} \times 100 \tag{3}$$

where W_1 and W_2 are the masses of the wet and dry samples.

The porosity p of any porous material is a measurement of the total pore space that can be occupied by water in that material and can be expressed as % given by [36]

$$\text{porosity} = \frac{V_w - V_d}{V_w} \times 100 \tag{4}$$

where V_d and V_w are the volume of dry and wet samples:

$$V_d = \frac{\text{Weight of the dry samples}}{\text{Density of the soil grain}} \tag{5}$$

The diffusion equation of radon through soil, with an assumption that the medium is without source, is given by [36]

$$\frac{D_e}{p}\frac{d^2C}{dx^2} - \lambda C = 0 \tag{6}$$

where C is the concentration of the gas, λ is the decay constant of the gas in s^{-1}, D_e is the effective diffusion coefficient of the gas in the porous medium in $cm^2\ s^{-1}$ and p is the porosity of the medium.

The solution of Eq. (6) is

$$C(x) = C_\circ \exp\left(\left(-\sqrt{\frac{\lambda p}{D_e}}\right)x\right) \tag{7}$$

where $C(x)$ is the concentration of radon at any time t at a distance x, C_o is the concentration of the radon in the source and $D_e = D \times p$ where D is the diffusion coefficient. Relations between the radon concentration in soil and the indoor radon concentration are rather complicated. Nevertheless, the data on radon concentration in the soil is the starting point for the assessment of the expected radon on the constructed building. It was shown that the most relevant soil parameters on the radon flux at the top of the crack are, in this case, effective diffusion coefficient, soil gas permeability and deep soil radon concentration [38, 39]. Radon concentration from an infinite column of soil as a function of distance z into soil is given by [40]

$$C(z) = C_\infty\left(1 - \exp(-z/d)\right) \tag{8}$$

where $d = \sqrt{D/\lambda}$, λ is the decay constant, D is the diffusion constant and C_∞ is the concentration at infinite depth.

2.4. Building material sources

Radon emitted from building materials. The natural building materials with higher radium content are of large concern. The type of aggregate material, water and natural gas contribute significantly in an indoor concentration levels. This may depend on the consumption rate and the origin of the source. Measurements of radon exhalation rates could be done by both active and passive techniques [7].

2.4.1. Calculation of radon concentration and radon exhalation rates

For the purposes of calculating ^{222}Rn concentration and radon exhalation rate, when the study was conducted by using the passive diffusion dosimeter, the surface exhalation rate of radon E_x (Bq m^{-2} h^{-1}) is determined by Eq. (9), as [12, 13]

$$E_x = \frac{\lambda VC}{A\left[T + \lambda^{-1}\left(\exp(-\lambda T) - 1\right)\right]} \tag{9}$$

The mass exhalation rate of radon E_M (mBq kg^{-1} h^{-1}) is determined by using the following (Eq. (10)) [7, 13]

$$E_M = \frac{\lambda VC}{M\left[T + \lambda^{-1}\left(\exp(-\lambda T) - 1\right)\right]} \tag{10}$$

where C is the calculated integrated radon exposure as measured by SSNTDs in (Bq m^{-3} h), T is the exposed period of the detector (hours), V is volume (m^3), λ is the decay constant of radon (h^{-1}), A is the surface area (m^2) and M is the sample's mass (kg).

2.5. Water sources

Radon and radium in water are exposed by either ingestion from the daily consumption of water or by inhalation through the daily routine use of water. They constitute a health risk for inhabitants [5, 41]. Due to clathrate behaviour, the solubility of radon decreases with temperature, but temperature dependence is much stronger for heavier gases. Radon can be transported by groundwater to far larger distances than by diffusion process in a short time [42].

2.5.1. Calculation of radon activity density from water samples

The radon activity density in water C_w was calculated using the formula [43, 44]

$$C_W = \frac{\lambda Cht}{L} \tag{11}$$

where λ is the decay constant of radon-222, h is the distance from the surface of water in the sample can to the detector, t is the exposure time of the sample and L is the depth of the sample.

The time elapsed for the sample collection and analysis is corrected using the following equation:

$$C_W = C_0 e^{-\lambda t} \tag{12}$$

where C_W is the measured concentration, C_0 initial concentration (to be calculate) after the decay correction and t is the time elapsed since collection (days), λ = 0.181, $t_{1/2}$ = 3.83 days.

2.6. Dispersion in air

The dispersion of radon in air is influenced by the vertical temperature gradient, the direction and strength of the wind and the air turbulence [45]. The dispersion of radon daughters is also influenced by precipitation and washout ratios. The radon progeny concentrations and washout ratios are inversely correlated with low precipitation intensities [46]. It was found that the correlation between radon concentration and wind speed shows a broad inverse correlation.

The explanation of this correlation is the dispersion of radon in a larger volume due to vertical mixing under stable atmospheric conditions and the dural variations. It was also found that the effect of turbulence drops the radon concentration using a mixing fan [47].

2.7. Mines and mine tailings

Sources of radon of local interest include the tailings from uranium mining, milling and geothermal power stations. The radon exhalation rate from tailings depends on the radon content of the tailings, the emanation factor and the land reclamation [48]. The required uranium is mined in the form of uranium oxides; the richer ores contain some 1–4 kg uranium per 1000 kg of ore [49]. Mining of all kinds affects the environment negatively. In the area of mining, the specific concerns are the occupational radiation exposure of miners and population living in the vicinity of the mining area. Miners are exposed to airborne radon and its short-lived decay products, alpha emitters and gamma dose rate. Radon emanation from a uranium mine is an important pathway for public radiation exposure [50]. The tailings consist of residues with still enough uranium to produce radon gas escaping into the surroundings; in fact 85% of the radioactive materials of the ore are still in tailings [49].

2.8. Natural gas and crude oil

In nature, the sources of oil and gas are sedimentary rocks, namely, sands, sandstone, grills, limestone and dolomites. The sedimentary and igneous rocks also contain trace amounts of uranium-238 in varying quantities which is the source of radon [23]. With the oil exploration, ^{238}U may also be extracted, which is present in crude oil and natural gas.

Facilities producing natural gas and condensate are mainly affected by radon and one of its decay product polonium-210, with half-life of 138.4 days. The boiling point of radon is approximately 62°C, and it will tend to follow gases of similar boiling point (ethane and propane) through the separation circuits. Radon will progress through the facility in the gas stream, by its decay products, which tend to plate-out on pipelines and vessel surfaces. The 138.4-day half-life of polonium-210 allowed this radionuclide to build to sometimes very high levels, which can only be detected by using alpha particle monitoring instruments. Radium and its decay products can also present in silt materials deposited in the separator, dehydration and drying units and condensate recovery vessels. Some facilities use a polonium treatment unit during condensate recovery to remove polonium isotopes, and the polonium concentrations in these units can become very high over a period of years of operation [51].

In oil production both radon gas and its direct precursor radium-226 can be a problem. Radon in the stream will be separated by the gas scrubbers. The problem is similar to the gas plant, in that polonium-210 will plate-out on an available surfaces. However, radium-226 can also be present as a dissolved solid and will act with another chemical in the liquid phase, to form insoluble compounds, which are deposited as a scale in pipe work and vessels. This scale can be detected by gamma radiation monitors externally but may be misleading with alpha radiation, because of the deposition of polonium-210 from radon. Scale can be presented in all areas of the process plant and will gradually increase with time. In some cases, the radioactivity of scales and silts is high enough to warrant that they be deposited of low specific activity radioactive wastes [51].

2.9. Dose estimation and lung cancer risk

Regarding radiation dose to the public, due to waterborne radon, it is believed that waterborne radon may cause higher risk than all other contaminants in water. Therefore, radon in water is a source of radiation dose to stomach and lungs. The annual effective doses for ingestion and inhalation were calculated according to parameters introduced by UNSCEAR report [1].

The annual effective dose due to inhalation corresponding to the concentration of 1 Bq L^{-1} in tap water is 2.5 μSv y^{-1}. In the UNSCEAR, 2000, report, the annual effective dose rate E_{Eff} could be calculated using the following (Eq. (1)):

$$E_{Eff}\left(\text{mSv y}^{-1}\right) = C_{Rn}\left(\text{Bq m}^{-3}\right) \times 8760\left(\text{h y}^{-1}\right) \times 0.4 \times 0.8 \times 9.0 \times 10^{-6}\left(\text{Bq m}^{-3}\,\text{h}^{-1}\right) \quad (13)$$

The annual effective dose rate was also related to the average radon concentration C_{Rn} by the following expression [1, 7]:

$$E_{Eff}\left(\text{WLM y}^{-1}\right) = \frac{8760 \times n \times F \times C_{Rn}}{170 \times 3700} \quad (14)$$

where C_{Rn} is the radon concentration in Bq m^{-3}, n is the fraction of time spent indoors, F is the equilibrium factor, 8760 is the hours per year and 170 is the hours per working month. For purposes of the effective dose equivalent estimation, a conversion factor of 6.3 mSv WLM^{-1} should be used [1].

The annual effective dose to an individual consumer due to intake of radon from drinking water is evaluated using the relationship [3]:

$$E_W\left(\text{Sv y}^{-1}\right) = C_W \times C_{RW} \times D_{CW} \quad (15)$$

where E_w is measured in (Sv y^{-1}), C_w is the concentration of radon in water (Bq L^{-1}), C_{Rw} is the annual consumption of water (L y^{-1}) and D_{cw} is the dose conversion factor for radon (Sv Bq^{-1}). Following exposure of radon from consumed water, annual effective doses (μSv y^{-1}) and effective doses per litre (nSv L^{-1}) could be calculated [3].

The relative risk of lung cancer (RRLC) due to indoor exposure to radon should be calculated by using the following formula [29, 52]:

$$\text{RRLC} = \exp(0.00087352\ C_{Rn}) \quad (16)$$

3. Materials and methods

3.1. Introduction

A wide range of techniques for the detection and quantification of radon and its daughters have been developed over the last few years. There is no a single technique that can meet all

the requirements of the different types of the radon measurements. The choice of the most appropriate one depends on the particular information needed, the type of radon surveys and the cost of the apparatus. For example, a large number of long-term integrated measurements are needed for the measurements of the population exposure to radon, while continuous radon monitoring is required to study the dependence of the soil radon on the environmental and geophysical parameters.

3.2. Short-term radon measurements

Short-term measurements (from a few days to 1 month) are particularly for screening surveys to identify houses with high radon concentrations and to investigate the geographical variations. When such short-term measurements are employed for the assessment of radon exposure in dwellings, particular care is needed to define a protocol of exposure. To this end, activated charcoals, electret ion chambers (EICs) and solid state nuclear track detectors (SSNTDs) are the most attractive techniques.

Different attempts have been made to improve the response of activated charcoal devices, especially with the use of diffusion barrier to decrease the effect of humidity. With the electret ion chamber (EIC) devices, the most important limitation is their sensitivity to gamma radiation, which, however, can be easily corrected with any means including an additional radon proof electret ion chamber. SSNTDs are not efficiently sensitive for short-term measurements. This limitation is due essentially to the small area normally counted. Another alpha track detector, which is not sensitive to the plate-out, is polycarbonate and can be conveniently used as a bare detector [53].

3.3. Long-term radon measurement

The most representative measurements of the true exposure of radon gas in any environment are the long-term (up to 1 year) integrating types of measurements.

The most commonly used detectors are, respectively, SSNTDs and electrets. These detectors are used as bare detectors or in combination with closed radon samplers. The most established geometry for a closed radon sampler consists in a chamber with a porous filter such as fibre glass, a non-wetting cloth or a micropore paper filter [54] and one or more SSNTDs. These filters, which are used to stop external radon daughters, do not discriminate thoron gas and water vapour.

3.4. Active and passive measurement

The measurements of radon/radon daughters by passive techniques are based on the detection of their radioactive decay.

There are different ways to define active and passive types of radon measurement systems. The classification, which seems to avoid any possible confusion, is reported in the following:

3.4.1. Active instrumentation and/or methods

The sampling of radon/radon daughters is made by forced sampling through the use of power supply (pumps).

3.4.2. Passive instrumentation and/or methods

The sampling of radon/radon daughters is based on the natural diffusion without any power supply. Another important classification can be introduced according to the type of radiation detector used:

- Detectors with real-time response (typically scintillators and semiconductors).
- Detectors with no real-time response (e.g. track-etched detectors, activated charcoal and electrets).

In practice a radon/radon daughter monitor may be formed by any possible combination of active or passive sampling systems and real-time or no real-time detectors.

3.5. Methods of measurements of radon gas concentration

Radon measurement techniques are performed for different applications. The radon concentration in air is highly dependent on several factors, mainly the air ventilation. The various detectors one can put in a bore hole for radon concentration measurements are essentially solid state nuclear track detectors, daughter collectors such as alpha card, electret detectors and thermoluminescent phosphors and solid state electronic detectors such as photodiode and gas absorber like activated charcoal [55].

3.5.1. Direct measurements

Passive sampling can be combined with real-time detectors for direct (not integrated) or continuous measurements. For example, in the continuous passive radon detectors, radon diffuses through a filter in a ZnS (Ag)-coated cell optically coupled with a photomultiplier tube. Passive sampling is followed by electrostatic collection in combination with scintillation discs and photomultiplier tube or silicon surface barrier detectors [56].

Within the silicon technology several new devices, such as random access memories (RAMs), photodiodes or charged coupled devices (CCDs), although developed for different applications, can be conveniently used for alpha particle detection and for radon monitoring. The low power requirements, the low cost and the high reliability of these devices make them uniquely interesting for passive radon monitoring [57].

3.5.2. Passive absorption measurements

Radon gas can be collected by adsorption on activated charcoal and then measured using gamma detectors or liquid scintillation technique passive detectors as thermoluminescent detector (TLD) can also be used in combination with activated charcoal. Short-term integrating monitoring using activated charcoal has been extensively employed in large surveys [58].

3.5.3. Passive diffusion, electrostatic collection and passive detectors

In this system radon is sampled by diffusion in a chamber, and its daughters are collected by an electrostatic field on aluminized Mylar film facing the scintillation disc of ZnS (Ag). The alpha particle that induced the scintillations is registered by photographic films, a similar passive system referred to as Environmental Gamma Ray and Radon Detector (EGARD) has been reported by Maiello and Harley [59], in which system the radon daughters are collected through an electret-induced electric field and registered by a thermoluminescent detector (TLD).

3.5.4. Passive sampling and passive detectors

Totally passive devices can successfully be obtained for radon-only measurements in which radon diffuses through a filter or a membrane in a detector housing, and the radiations from the radon daughter produced are directly registered by passive type of detectors.

Different types of passive detectors can be used such as thermoluminescent materials, electret devices and solid state nuclear track detectors (SSNTDs). With respect to large-scale surveys, SSNTDs have the most favourable characteristics for radon measurements and their applications. The most often used track detectors available for the registration of alpha particle are essentially cellulose nitrate (typically the red-dyed LR-115), bisphenol-a poly carbonate (Makrofol or Lexan) and allyl diglycol carbonate (CR-39). CR-39 nuclear track detector method is based on letting air diffuses in a holder where alpha particles are detected by means of a solid state nuclear tack detector [60].

3.6. Physical bases of radon gas measuring techniques

3.6.1. Solid state nuclear track detectors

Basically, solid state nuclear track detectors (SSNTDs) work as follows:

The passage of heavily ionizing particles, such as alphas, through most insulating solids creates narrow paths of intense damage on an atomic scale. These damage trails may be enlarged until they can be seen under an optical microscope, by chemical treatment that rapidly and preferentially removes the damaged material. It removes less rapidly the surrounding undamaged matrix in such a manner as to enlarge the etched tracks that mark and characterize the site of the original damaged region [61]. SSNTDs are sensitive to alpha particles but totally insensitive to beta and gamma rays. They do not require energy to be operated and unaffected by humidity, low temperature, moderate heating and light. After irradiation, SSNTDs are chemically processed, and the determination of the number of particles that have impinged the detector can be performed by various means. The most common is the counting of the tracks under an optical microscope, but many other techniques have been devised [61].

3.6.2. Alpha card

According to its producer alpha nuclear, the alpha card system is a passive radon detecting method, which provides a sensitive measure of radon in gaseous state. The card is deposited in the ground, suspended in an inverted cup. It is left in place from 12 h up to several days. After

entering the volume of detection, the radon decays away, and its daughters make an active deposit on a thin membrane. The alpha card is then recovered and read. The reading device contains two silicon detectors, sensitive to alpha particles only, facing one another and between which the card is inserted. In this manner a good counting efficiency is achieved. The reader is small, portable equipment that can be used in the field.

3.6.3. Electret detectors

One of the most recent techniques is the electret radon monitor. The electret dosimeter offers several advantages: its ability to store information over a relatively long period, its independence of the humidity in its environment and its easiness of reading. But its response curve does not cover efficiently the very low or very high doses, and also it is sensitive to gamma radiation background, which in some cases induces significant error or even precludes their uses.

3.6.4. Activated charcoal

The adsorption of radon could be measured in an activated charcoal using a plastic can. The dosimeter should be replaced in the location where measurement is intended, lid open and left in place for 4–12 days. It is then retrieved and the lid closed and brought to the lab where the gamma activity is determined.

3.6.5. Thermoluminescent detectors (TLDs)

Based upon the principle of light emission after heating, several thermoluminescent dosimeters (TLDs) have been constructed and improved. The idea of detecting radon by using these dosimeters is depending on the ability of recording the alpha activity of the radon daughters. After a suitable exposition, the TLD is recovered and "read" in a TLD reader [62].

3.6.6. Solid state electronic detectors

Electronic detectors for radon measurements in the soil are not widely used because they usually require energy and also they are rather expensive and fragile. One may mention the alpha-metre manufactured by Alpha Nuclear Company; the active part of the equipment is a Si (Li) detector associated with a counter unit. The counting is directly displayed on the instrument.

Using photodiode simple equipment that can be operated on pen-type batteries for a year has been developed. The detector does not require a polarization voltage, and the simplifying electronics is a very low consumption setup. Data are stored in memory cards of a microcomputer. The main advantage of electronic equipment of this type is that they allow dynamic studies of low term variations on the radon concentration [63].

3.6.7. Pylon chamber

Filtered air is pumped into an electrostatic chamber in which the negative electrode is made of a thin conductive Mylar foil placed on a ZnS scintillator for alpha particle detection. Three

hours after the end of sampling, the alpha particles emitted by radon and radon daughters are counted [63].

3.6.8. Solid state alpha spectrometry

A known volume of air is forced through a filter. The radon daughter's concentration in the air sample is measured through alpha spectrometry on the filter using a solid state detector [63].

3.6.9. Active carbon detectors

Air diffuses in a canister where radon gas is adsorbed by active carbon. Sampling lasts 2–4 days; later the gamma rays emitted by the radon progeny captured into the active carbon are counted by means of scintillation detector (ROLS, 4300E USA).

3.6.10. Lucas cells

Glass or transparent plastic holders (cells) internally coated with ZnS are used. Just before sampling the cell is evacuated. Then, the air to be sampled is filtered and let into the cell. After at least 3 h delay, the cell is placed in optical contact with a photomultiplier and alpha particles emitted by radon, and its daughters are counted. The sensitivity of the system is about 4 Bq m^{-3} [55].

3.6.11. Markov method

This method is based on two successive counting of alpha particles from a glass fibre filter through which a known air volume has been previously aspirated. This technique supplies the measure of the potential alpha energy concentration [63].

3.7. Sampling methods for the measurement of radon in air

Methods and instrumentation may be classified on the basis of the type of monitoring as grab sampling and continuous and time-integrating monitoring.

3.7.1. Grab sampling methods

3.7.1.1. Radon sampling and counting scintillation flask

The scintillation cell technique is one of the most widely used in various applications. The device consists essentially of a container with a transparent bottom coated internally with silver-activated zinc sulphide phosphor. The bottom is coupled to a photomultiplier tube and counting device. Cells sizes ranges from 0.10 to 2.0 L. The scintillation flasks can be filled either by evacuation or by airflow using a pump.

The lower level of detection (LLD) depends on several parameters, such as the size of flasks, type of material and counting intervals. For typical devices a sensitivity of 3.7 Bq m^{-3} is reported [63].

3.7.1.2. Ionization chambers

Ionization chambers are very complex laboratory instrument essentially used in laboratory as highly accurate measurement systems, which are directly traceable to reference standards. An ionization chamber consists of two conductors with a glass-filled space and an electric field applied between them. Pulses from collector are fed into the preamplifier and from here to a linear amplifier and scalar. The collector anode is connected to a device sensitive to voltage changes. The instrument can be operated either by alpha pulse counting or by ionization current measurement. Special techniques are used for filling the counter with filtered air to remove atmospheric aerosols including radon daughter products. Flow-through ionization chambers can be used for both laboratory applications, and as field instruments, sealed ionization chambers are essentially laboratory instruments. Samples are collected in the field and returned for laboratory assay where they are transferred ionization chambers for counting. To test performance and efficiency of the instruments, including the filling apparatus, a sample of radon is drawn from a standard source of ^{226}Ra. The theoretical sensitivity is of the order of 10–4 A Bq^{-1} at equilibrium Rn/Rn_D [63].

3.7.1.3. Two-filter method

The device consists of a cylindrical tube, which is fitted to both ends with filter holders and a pump to draw air. The first filter allows entering only radon and other atmospheric gases. The exit filter collects on the inside radon daughters formed within the chamber.

The activity of the outlet filter, which is proportional to the radon concentration in air, is measured by alpha counting devices: ZnS (Ag) scintillation detectors or solid state barrier detectors. The two-filter technique can be used for short-term sampling in workplaces or for continuous outdoor monitoring of very low levels of radon concentrations [63].

3.7.2. Continuous sampling instruments for radon air monitoring

Continuous monitoring of radon concentration is used both for research and radioprotection purposes. The main applications concern diagnostic of radon sources for remedial actions, the measurement of variations of ambient radon concentration and soil gas radon levels. Two different methods of sampling are generally used.

3.7.2.1. Diffusion sampling continuous radon monitor

The diffusion radon monitor is a device that does not require power supply for sampling, but makes use of electronic circuitry for counting alpha particles. Radon gas enters into the volume of the instrument by molecular diffusion through a filtering device.

Radon progeny resulting from the decay of radon within the sensitive volume is counted by scintillation or a surface barrier detector. To improve sensitivity Rn_D atoms can be focused of the detector surface with an electrostatic collector. The efficiency of the electrostatic collection depends on particle motilities, which are reduced by the aggregation of water molecules around the ions in the humid atmosphere. Beds of silica gel are used to make these devices independent of the moisture content of the air [63].

3.7.2.2. Flow-through sampling continuous radon monitor

Air is drawn continuously through double stopcock scintillation flask by an air pump. The total counts registered in a given interval are a function of the radon concentration, the activity of daughters collected during the interval and the activity of RnD collected during previous intervals. This effect is of particular importance in the presence of rapid variation of radon concentration. With changing radon concentration, the radon progeny build-up inside the scintillation flasks should be taken into consideration during the calibration. This effect requires a correction if instruments are calibrated with steady-state radon concentrations. Calibration factors could overestimate or underestimate real radon concentrations. A special device based on a solid state barrier detector was developed for monitoring fast changes of radon concentrations [64].

3.8. Time-integrating radon monitors

The time-integrating monitors measure the average radon concentration during the exposure period. Various devices have been developed based on the diffusion of radon into a sensitive volume through a filtering device and the measurement of radiations emitted by radon and its progeny using as active counting devices either scintillation ZnS (Ag) or silicon surface barrier detector [65].

3.9. Radon monitoring in soil

Plastic track detectors, viz. cellulose nitrate films (LR-115 type 2) manufactured by Kodak-Pathe, France, and CR-39 sheets (Pershore Moulding Co., UK), are very sensitive for recording alpha particle tracks produced by radon. Plastic track detectors are capable of recording average value of radon isotopes over relatively longer periods (weeks to months) but are insensitive to transient variations that last only several hours or less.

3.9.1. Track-etch method

Track-etch technique is quite appropriate for radon detection in the soil gas because of its negligible background of spurious signals, low cost, ruggedness and nature as an integrating measurement. The detector assembly rests in the vertical position near the bottom of auger hole and radon decay alpha particles impinge on the detector films leaving their radiation damage trials. LR-115 films could be collected after a week or month, as the case may be, and etched in a constant temperature bath using 2.5 N NaOH solutions for 2 h at 60°C. Alpha tracks are revealed as circular or conical spots, which become etched-through holes after prolonged etching. The track spots or holes would be counted using a binocular microscope under a suitable magnification. The measured track density is assumed to be proportional to the average radon content in soil gas [66].

3.9.2. Radon emanometry

Radon emanometer (type RMS-10) is used to measure the instantaneous radon concentration in the soil gas. The apparatus consists of an alpha counting scintillation assembly with inverted

bell-shaped alpha detector, a hand-operated rubber pump and a soil-gas probe. The probe is metallic tube about 4 cm diameter, with perforations at the lower end and a rubber capping at the top to seal it pneumatically in an auger hole. It has inlet and outlet tubes for the circulation of the soil gas. The hand-operated rubber pump is used to circulate the soil gas into the scintillation chamber. The alpha particles emanating from the radon impact the ZnS (Ag) scintillators creating an energy impulse in the form of light quanta, which are recorded by scintillation assembly [67].

3.9.3. Silicon-diffused junction detector

Alpha metre-400 is designed to measure near surface radon gas fluctuations. It consists of silicon-diffused junction for detection of alpha particles and gives sufficient counts over 24 h exposures in most of the soils. The detector unit is placed inside a covered auger hole about 60 cm in depth. The detector is separated from the soil surface at the bottom of hole by a 6.4 cm gap, which shields the detector from the impact of the direct alpha particles emanated by radon isotopes and their alpha emitting daughters [68].

3.10. Radon monitoring in groundwater

Radon emanometry technique has been used for groundwater radon measurements. The radon content is determined by measuring radon-generated alpha activity in discrete water samples collected once a day from the monitored wells and natural springs.

3.10.1. Radon measurements in groundwater using RAD7

Radon measurement of groundwater samples could be used by radon-in-air monitor RAD-7. The monitor is used to determine radon-in-air activity concentrations by detecting the alpha-decaying radon daughters (Po-218 and Po-214) using a passivated implanted planar silicon detector (PIPS). At the end of the run, the RAD7 prints out a summary, showing the average radon reading [21].

4. Conclusions

From our study we can conclude that, we have mentioned the most important information about radon throughout the environment, the health importance of prompt radon daughters, the radon problem, the risk of lung cancer and the radon measuring techniques. Then we discussed the main sources of radon in the environment (indoor, soil, building materials, water, etc.) and the techniques used for measuring radon in the environment including long-term and short-term radon measurements and active and passive measurements; then we summarizes the methods of measurements of radon gas concentration, physical basis of radon gas measuring techniques, sampling methods for the measurement of radon in the air, time integrated radon monitors, radon monitoring in soil, radon monitoring in groundwater and passive diffusion radon dosimeters (CR-39). This chapter presents the essential and important information in a concise manner in order to clarify the importance of radon gas in the environment.

Author details

Abd Elmoniem Ahmed Elzain[1,2]*

*Address all correspondence to: moniemelzain1@yahoo.com

1 Department of Physics, Kassala University, Sudan

2 Department of Physics, College of Science and Arts in Oqlat Alsqoor, Qassim University, Saudi Arabia

References

[1] UNSCEAR. United Nations Scientific Committee on the Effects of Atomic Radiations, Sources and Effects of Ionizing Radiation, Vol. I Annex A: Dose Assessment Methodologies, United Nations, New York; 2000

[2] ICRP, International Commission on Radiological Protection Against Radon-222 at Home and at Work; ICRP Report 65, Pergamon: Oxford; 1993

[3] UNSCEAR. United Nations Scientific Committee on the Effects of Atomic Radiations, and effects of ionizing radiation. Report to the General Assembly, with Scientific Annexes, United Nations, New York; 1993

[4] Elzain AEA. A study of indoor radon levels and radon effective dose in dwellings of some cities of Gezira State in Sudan. Nuclear Technology and Radiation Protection. 2014; **29**(4):307-312

[5] Elzain AEA. A study on the radon concentrations in drinking water in Kassala State (Eastern Sudan) and the associated health effects. World Applied Sciences Journal. 2014;**31**(3):367-375

[6] Elzain AEA. Estimation of soil gas radon concentration and the effective dose rate by using SSNTDs. International Journal of Science and Research Publications (IJSRP). 2015;**5**(2): 3887-3891

[7] Elzain AEA. Radon exhalation rates from some building materials used in Sudan. Indoor and Built Environment. 2015;**24**(6):852-860

[8] Idriss H, Salih I, Abdulaziz AS, Abdelgalil MY, Salih SA, Hasan AM, ELtahir MA, Ahamed MMO. Study of radon in soil gas, trace elements and climatic parameters around South Kordofan state, Sudan. Environmental Earth Sciences. 2014;**72**(2):335-339

[9] Nazaroff WW, Nero, Jr. AV. Radon and its Decay Products in Indoor Air. New York: John Wiley and Sons; 1988

[10] Akerblom G, Wilson C. Radon-Geological Aspects of an Environmental Problem. Report No. 30. Uppsala: Geological Survey of Sweden; 1982

[11] Elzain AEA. Determination of radium concentration and radon exhalation rate in soil samples using CR-39. Advances in Applied Science Research. 2015;**6**(2):92-102

[12] Elzain AEA, Mohammed, YSh, Mohamed KhSh, Mohamed-Ali AM. A study of radium concentration and radon exhalation rate in soil samples from Kassala Town, Sudan using SSNTDs. American Journal of Physics and Applications. 2016;**4**(4):84-89

[13] Elzain AEA, Mohammed YSh, Mohammed KhSh, Sumaia SM. Radium and radon exhalation studies in some soil samples from Singa and Rabak Towns, Sudan using CR-39. International Journal of Science and Research (IJSR). 2014;**3**(11):632-637

[14] Abu-Jarad F. Application of nuclear track etch detector for radon related measurements. International Journal of Radiation Applications and Instrumentation Part D Nuclear Tracks and Radiation Measurements 1988;**15**(1):525-534

[15] Khan AJ, Parasad R, Tyagi RK. Measurements of radon exhalation rate from some building materials. Nuclear Tracks and Radiation Measurements. 1992;**20**(4):609-610

[16] Yu KN, Chan TF, Young ECM. The variation of radon exhalation rates from building surfaces of different ages. Health Physics. 1995;**68**(5):716-718

[17] Karpińska M, Jacek K, Zenon M, Andrzej S. Radon in drinking water in the Białystok region of Poland, NUKLEONIKA. 2010;**55**(2):177-180

[18] Mowlavi AA, Shahbahrami A, Binesh A. Dose evaluation and measurement of radon concentration in some drinking water sources of the Ramsar region in Iran. Isotopes in Environmental and Health Studies. 2009;**45**(3):269-272

[19] WHO. Guidelines for Drinking Water Quality. 3rd ed. Geneva; 2008

[20] Abdul Kader Arafin SK. Radon concentration in shallow and deep tube-well water samples using SSNTD method. Online Journal of Physical and Environmental Science Research. 2012;**1**(1):1-4

[21] Badhan K, Mehra R and Sonkawade RG. Measurement of radon concentration in ground water using RAD7 and assessment of average annual dose in the environs of NITJ, Punjab, India. Indian Journal of Pure and Applied Physics. 2010;**48**(7):508-511

[22] Nikolov J, Todorovic N, Forkapic S, Bikit I, Mrdja D. Radon in drinking water in Novi Sad. Proceedings of World Academy of Science, Engineering and Technology. 2011;**76**: 307-310

[23] UNSCEAR. Exposure to Radon and Thoron and Their Decay Products. Report to the General Assembly, Annex D. United Nations, New York, USA; 1982

[24] Alshahri F and Alqahtani M. Radon concentrations and effective radium contents in local and imported phosphate fertilizers, Saudi Arabia. Arabian Journal for Science and Engineering. 2015;**40**:2095-2101

[25] Mukhtar OM, Elzain AEA. Radon monitoring at Khartoum using the charcoal technique. Abhath al-Yarmouk. Basic Sciences and Engineering. 2006;**15**(2):225-235

[26] Espinosa G, Gammage RB. Long-term radon survey in Mexico City and other regions of the country. Radiation Measurements. 1997;**28**(1-6):663-665

[27] Alter HW, Price PB. Radon detection using track registration material. US Patent, 3, 665, 194 Terradex Corp; 1972

[28] Elzain AEA. Indoor Radon-222 concentrations in some Cities in Kassala State, Eastern Sudan. In: Proceedings of the 2011 International AASRT Symposium, Orlando, Florida, USA. Vol. 2; 2011. pp. 71-84

[29] Elzain AEA. Measurements of indoor radon levels and dose estimation and lung cancer risk determination for workers in health centres of some towns in the Sudan. American Journal of Modern Physics. 2016;**5**(4):51-57

[30] Nazaroff WW. Radon transport from soil to air. Review of Geophysics. 1992;**30**(2):137-160

[31] NCRP. Exposure from Uranium Series with Emphasis on Radon and its Daughters. Bethesda, MD: National Council on Radiation Protection and Measurements, Report No. 77; 1984

[32] UNSCEAR. Sources, Effects and Risks of Ionizing Radiation. United Nations Report, New York, U.S.A: United Nations Publications E. 94 IX. 11; 1988

[33] ICRP. International Commission on Radiological Protection, Recommendations of the International Commission on Radiological Protection, ICRP Publication 26, Annals of the ICRP, 1(3), Pergamon Press, Oxford; 1977. pp. 11-13

[34] Abu-Jarad F, Fremlin JH. Effect of internal wall covers on radon emanation inside houses. Health Physics. 1983;**44**(3):243-248

[35] Minkin L. Is diffusion, thermodiffusion, or advection a primary mechanism of indoor radon entry? Radiation Protection Dosimetry. 2002;**102**(2):153-161

[36] Shweikani R, Giaddui TG and Durrani S. The effect of soil parameters on the radon concentration values in the environment. Radiation Measurements. 1995;**25**(1-4):581-584

[37] Gundersen LCS. The effect of rock type, grain size, permeability and moisture content on radon on soil gas. Journal of Radioanalytical and Nuclear Chemistry. 1992;**161**:325-337

[38] Mazur D, Janik M, Loskiewicz J, Olko P and Swakon J. Measurements of radon concentration in soil gas by CR-39 detectors. Radiation Measurements. 1999;**31**:295-300

[39] Albarracín D, Font LI, Amgarou K, Domingo C, Frenández F and Baixeras C. Effect of soil parameters on radon entry into a building by a means of the TRANSRAD numerical model. Radiation Protection Dosimetry. 2002;**102**(4):359-364

[40] Flischer RL and Magro-Campero A. Mapping of integrating radon emanation for detection of long-distance migration of gases within the earth: Techniques and principals. Journal of Geophysical Research. 1978;**83**(B7):3539-3549

[41] Cross FT, Harely NH and Homann W. Health effects and risks from radon-222 in drinking water. Health Physics. 1985;**48**:649-670

[42] Menin A, Drigo A, Capra E and Verri G. Radon monitoring in dwellings and in water in localized areas of Friuli-Venezia Giulia (Italy). In: Furlan G and Tommasino L, editors. Proceedings of the 2nd Workshop on Radon Monitoring in Radioprotection, Environmental and/ or Earth Sciences, ICTP, Trieste, Italy, 1991, Singapore: World Scientific; 1991. pp. 79-87

[43] Somogyi G, Hafez A, Hunyadi I and Toth–Szilagyi M. Measurement of exhalation and diffusion parameters of radon in solids by plastic track detectors. Nuclear Tracks And Radiation Measurements. 1986;**12**(1-6):701-704

[44] Elzain AEA. Measurement of radon-222 concentration levels in water samples in Sudan. Advances in Applied Science Research. 2014;**5**(2):229-234

[45] Akber RA, Pfitzner J and Johnston A. Wind direction correlated measurements of radon and radon progeny in atmosphere: A method for radon source identification. Radon and Radon Progeny in Australia. Symposium, Canberra; 1994; 18 Feb. pp. 55-63

[46] Paatero J. Wet deposition of radon-222 progeny in Northern Finland measured with an automatic precipitation gamma analyser. Radiation Protection Dosimetry. 2000;**87**(4): 273-280

[47] Abu-Jarad F and Sextro RG. Reduction of radon progeny concentration in ordinary room due to the mixing fan. Radiation Protection Dosimetry. 1988;**24**(1/4):507-511

[48] IAEA. Measurements and Calculations of Radon Releases from Uranium Mill Tailings. Technical Report Series No. 333. Vienna: International Atomic Energy Agency; 1992

[49] Egbert B and Rienk Van G. Environmental Physics. England: John Wiley & Sons Ltd.; 1995

[50] IAEA. The Application of the Principals for Limiting Release of Radioactive Effluents in the Case of Mining and Milling of Radioactive Ores. Safety Series No. 90. Vienna: International Atomic Energy Agency; 1989

[51] Chandler WP. Radon gas in oil and natural gas facilities. Radon and Radon Progeny in Australia. Symposium, Canberra; 1994; 18 Feb. pp. 71-75

[52] Elzain AEA, Sam AK, Mukhtar OM, Abbasher MA. A survey of indoor radon-222 concentration measurements in Kassala Town, Gezira. Journal of Engineering & Applied Sciences. 2008;**3**(2):72-100

[53] Rannou A, Jeanmarie L, Tymen G, Mouden A, Naour E, Parmentier N, Renouard H. Use of cellulose nitrate as radon and radon daughter detectors for indoor radon measurements. Nuclear Tracks and Radiation Measurements. 1986;**12**:747-750

[54] Fleischer RL. Radon in the environment—opportunity and hazards. Nuclear Tracks and Radiation Measurements. 1988;**14**(4):421- 435

[55] Bam BB, Bassigani A, Finazzi P, Giacomlli G, Lembo L, Maltoni G, Partizii L, Predieri F, Sartorio C, Serra P, Steinberg R, Togo V. Radon measurement in the Gran Sasso

underground laboratory. In: Furlan G, Tommasino L, editors. Proceedings of the 2nd Workshop on Radon Monitoring in Radioprotection, Environmental and/or Earth Sciences; 25 Nov.-6 Dec. 1991; ICTP, Trieste, Italy. Singapore: World Scientific; 1991. pp. 492-498

[56] Negro VC, Watnick S. FUNGI—A radon measuring instrument with fast response. IEEE Transactions on Nuclear Science NS. 1978;**25**:757

[57] Shott JV. Ionizing particle detection by charged coupled devices (CCDs). In: Furlan G, Tommasino L, editors. Proceedings of the 2nd Workshop on Radon Monitoring in Radioprotection, Environmental and/or Earth Sciences; 25 Nov–6 Dec. 1991; ICTP, Trieste, Italy. Singapore: World Scientific; 1991. pp. 257-268

[58] Prichard HM, Marien K. Desorption of radon from activated charcoal into a liquid scintillator. Analytical Chemistry. 1983;**55**:155

[59] Maiello ML, Harley NH. EGARD: An environmental gamma-ray and radon detector. Health Physics. 1987;**53**:301

[60] Beozzo M, et al. Measurement of indoor radon levels in Bologna metropolitan area. In: Proceedings of the 15th International Conference on; Particle Tracks in Solids, Marburg, Germany; 1990. p. 297

[61] Fleisher RL, Price PB, Walker RM. Nuclear Tracks in Solids-Principles and Application. Berkeley: University of California Press; 1975

[62] Yamamoto K, Fujii Y, Icotooka Y, Katayama T., Highly stable silicon pin photodiode, Nuclear Instruments and Methods in Physics A. 1987;**253**:542-547

[63] Bochicho F, Risica S. Active radon and radon daughter monitors. In: Tommasino L, Furlan G, Khan AH, Monnin M. editors, Proceedings of the Workshop on Radon Monitoring in Radioprotection, Environmental Radioactivity and Earth Sciences; April 3-14; ICTP, Trieste, Italy. Singapore: World Scientific; 1989. p. 110

[64] Wantick S, Latner N, Graveson RT. A radon-222 monitor using alpha spectroscopy. Health Physics. 1986;**50**:645

[65] Wrenn ME, Spitz H, Cohen N. Design of a continuous digital output environmental radon monitor. IEEE Transactions on Nuclear Science. NS. 1975;**22**:645

[66] Elzain AEA. Assessment of indoor radon doses received by the students and staff in schools in some towns in Sudan. International Journal of Science and Research (IJSR). 2015;**4**(1):2566-2571

[67] Ghosh PC, Bhalla NS. A close circuit technique for radon measurement in water and soil, with some of its applications. In: Proc. All India Symp. On Radioactivity and Metrology of Radionuclides, AEET, Bombay; 1966. p. 14

[68] Warren RK. Recent advances in uranium exploration with electronic alpha cups. Geophysics. 1977;**42**:982-989

IntechOpen