Correction of the effects of carbon dioxide and hydrogen sulfide on electrostatic cell monitors measurements of radon in water

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Abstract

The present study investigates the effect of two gases, hydrogen sulfide and carbon dioxide, on radon measurements in water using RAD7 electrostatic ion collector device. CO_2 concentrations between 0.65 g/l and 5.19 g/l were generated in water samples containing ^{222}Rn activities ranging from 23.4 ± 0.9 Bq/l to 6.7 ± 0.9 Bq/l, after which the samples were measured by RAD7 device and the results compared to the radon activity values of the gas-free samples. The same procedure was followed for hydrogen sulfide concentrations from 0.125 mg/l to 3 mg/l. In both cases, a major impact on the radon measured activity was observed, the apparent specific activities decreasing exponentially with gas concentration. For a CO_2 concentration of 1.29 g/l, the apparent specific activity underestimated the true value by 24.5%, while for a concentration of 5.19 g/l CO_2 the decrease was of 57%. For hydrogen sulfide, the radon measured values decreased by 42.5% for concentrations as low as 0.5 mg/l, culminating in a reduction of 86.9% for 3 mg/l H_2S. We are attributing these effects to ^{218}Po neutralization processes, which reduces the electrostatic efficiency of the silicon detector system. The results clearly show that application of correction methods are necessary when radon measurements are carried out on CO_2 and H_2S-rich waters using the RAD7

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28 device. To eliminate the interferences of these gases on RAD7 radon measurements, a sample

29 preparation method was developed and tested. This involves the precipitation and deposition

30 of CO_2 using $Ca(OH)_2$, and H_2S using $Pb(NO_3)_2$..

32

1. Introduction

34 Radon is a radioactive alpha emitting gas belonging to the natural radioactive decay

35 series of uranium. Radon-222 has a half-life of 3.8 days, and, from a radiological point of

36 view is the most important of the three naturally occurring isotopes of radon: [222]Rn (radon),

37 [220]Rn (thoron) and [219]Rn (actinon). Radon gas accounts for about half of the effective

38 radiation dose received from natural sources, the biologic effects being mainly attributed to

39 its short-lived alpha-emitting decay products ([218]Po and [214]Po). Radon in water causes

40 potential health risks first by elevating the radon concentration in indoor air, resulting in

41 inhalation of the gas, and secondly through ingestion (WHO, 2017).

42 Besides its radiological importance, accurate radon activity estimations can be used to

43 serve other purposes. As a geological tool, the radon monitoring technique can be used in the

44 study of active geological faults and geothermal energy sources (Khattak et. al., 2011). [222]Rn

45 is indicative of geothermal systems and water-rock relationships (Espinosa et. al., 1991), and

46 can also serve as an environmental tracer in single-well tests for estimating groundwater flow

47 velocities (Schubert et. al., 2011). Volcanic activity and magma degassing areas are known to

48 be correlated with groundwater radon anomalies (Segovia et. al., 1991).

49 In spring and geothermal waters, other naturally-occurring gases can be present

50 besides radon, such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S). Carbon dioxide is a

51 widely occurring gas in groundwater, and its highest concentrations can be found in mineral

52 waters as a result of dynamo- and thermo-metamorphism of carbonate rocks, as well as due to

53 biochemical reactions in sedimentary rocks. CO_2 can also interact with groundwater via

54 leakage pathways, such as direct leaks (abandoned wellbores), faults or fractures and diffuse

55 leaks such as permeable cap rock material and micro-fractures in the cap rock (Siirila et. al.,

56 2012). Depending on partial pressure and temperature, it generally attains a concentration of

57 up to 3 g/1 (Komatina, 2004). Hydrogen sulfide, another important gas present in

58 groundwater, can be produced through geothermal, volcanic activity, hot springs, and

59 underwater thermal vents (Giampaoli et. al., 2013). Sulfur gases that are released from the

60 ground can encounter groundwater and form hydrogen sulfide, whose concentration rarely

61 exceeds 50 mg/1 (Komatina, 2004). The necessity of studying both the effects of carbon

62 dioxide and hydrogen sulfide on RAD7 [222]Rn activity measurements is justified by the fact

63 that carbonated waters and hydrogen sulfide waters are constituting two out of six categories

64 of mineral waters. These two gasses are commonly found together, forming a third category,

65 namely H_2S-CO_2 waters (Komatina, 2004).

66 Several techniques have been used for radon in water measurements, either by using

67 passive methods, such as active charcoal measured by gamma spectrometry, as well as by

68 active measurement techniques such as Lucas cell scintillation (Nita et. al. 2014), liquid

69 scintillation counting (LSC) (Celaya et. al., 2018) and radon electronic detector devices such

70 as DURRIDGE RAD7 H_2O (Nikolov et. al., 2012) and Alpha GUARD (Elmehdi et. al.,

71 2019).

72 The Durridge RAD7 device is known to be widely used by researchers worldwide for

73 performing radon measurements in air, soil and water. The relatively low cost and ease of use

74 makes the device popular among researchers. It is important to know the influencing factors

75 which can lead to compromised results and erroneous interpretations. These factors can be

76 environmental (humidity, pressure, temperature), which have been studied in literature (Chu

77 and Hopke, 1988; Hopke, 1989; Roca et al., 2004), or other gases, beside radon. The effect of

78 carbon dioxide was previously investigated in air measurements using RAD7 device (Lane-

79 Smith and Sims, 2013) and found to be influencing the precision of the results, however no

80 study concerning its effect in water samples has been yet conducted, nor for the effect of

81 other commonly found gases. Besides, numerous studies already have been published

82 concerning the radon levels (measured by RAD7 device) in groundwaters (Duggal et. al.,

83 2013; Alharbi et al., 2015), geothermal waters and hot springs (Ertuğral et al., 2015; Ismail et

84 al., 2021) and drinking water (Salih, 2021). Following this statement, the investigation of the

85 effects of the most abundant gasses in water samples (CO_2 and H_2S) are mandatory for

86 correct and precise measurements performed with RAD7.

87 The aim of this study is to examine and quantify the effects of two gases present in

88 water, carbon dioxide and hydrogen sulfide, on the performance of DURRIDGE RAD7

89 electronic radon detector measurements in water, and to suggest a new protocol that increases

90 the accuracy for radon measurements in gas-rich waters by using this device. The present

91 study is the first work presenting such research results in the current literature.

92 **2. Materials and methods**

93

94 19 carbonated and 16 non-carbonated spring water samples from Covasna, Harghita,

95 Maramureș and Cluj counties, Romania were collected for performing routine measurements

96 of radon in water activity. The measurements were carried out employing two different

97 methods, namely Liquid Scintillation Counting (LSC) method using a TRICARB 2100 beta

98 spectrometer and the DURRIDGE RAD7 device.

4

99   The principle of the LSC method is based on the capture of ^{222}Rn in the scintillation

100   cocktail, and counting the scintillations produced by the cocktail due to the interaction of the

101   alpha and beta particles emitted by its short-lived daughters with it. Here, 10 ml of water

102   from each sample was directly inserted in glass vials containing 10 ml ProScint Rn A/B

103   scintillation cocktail. The vials were then shaken, after which the two phases (water and

104   cocktail) dissociated, and the radon gas remained trapped in the cocktail. The calibration of

105   the LSC device was performed using a RaCl$_2$ standard solution (NIST) dissolved in water and

106   having an activity of 6 Bq/l.

107   DURRIDGE RAD7 radon electronic detector is based on electrostatic collection of

108   alpha-emitters and spectral analysis. Both ^{218}Po (T$_{1/2}$=3.1 min) and ^{214}Po (T$_{1/2}$= 164.3 µsec)

109   alpha emissions are counted using a passivated ion-implanted Planar Silicon detector

110   (DURRIDGE RAD7 Manual). RAD7 is calibrated for two protocols, WAT40 and WAT250

111   which enables the user to perform radon measurements in water, using the H$_2$O accessories.

112   For the present study the WAT 250 protocol was used, which requires a sample volume of

113   250 ml. For confirmation, an LSC-RAD7 cross-test was performed on a water sample, and

114   identical values were obtained. The sample used did not contain any other gases beside radon.

115   The detection limit for the WAT250 protocol is 10 pCi/l (0.37 Bq/l), as stated in the RAD7

116   H$_2$O User Manual.

117   Prior to the radon activity measurements, the gas content of the samples was

118   determined using a simplified Scheibler method. An Erlenmeyer flask was filled with 350 ml

119   of sample and was attached to a Scheibler device, consisting of two graded burettes and a

120   buffer vessel. The instrument ensures constant pressure at the time of degassing. The samples

121   were magnetically stirred for twenty minutes, and as a result of the pressure of the released

gas, the water level in the burette rises. The volume of the released gas is indicated by the graded burette.

2.1. Laboratory procedure

To quantify the RAD7 measurement efficiency in water samples containing different amounts of gases, different concentrations of carbon dioxide and hydrogen sulfide were generated in the samples. In this regard, water samples were collected from a spring in Cluj County, Romania, which is known to have a relatively constant radon concentration. The samples were collected directly into RAD7 250 ml glass bottles. At the start of the experiment, three samples were measured by RAD7 to determine the radon activity in the absence of other gases. Subsequently, different quantities of CO_2 and H_2S were generated in water, and three measurements were performed for each concentration. Further experiments were performed for different radon concentrations in water after defined waiting times that allowed radon to decay.

2.1.1 Carbon dioxide experiments

To establish the effect of CO_2 on RAD7 radon activity measurements, carbon dioxide was generated in the water samples with concentrations ranging from 0.65 to 5.19 g/l CO_2. This was done by adding Na_2CO_3 and HCl in the water samples, CO_2 being formed, following the reaction:

$$(1) \ Na_2CO_3 + 2HCl \rightarrow 2NaCl + H_2O + CO_2$$
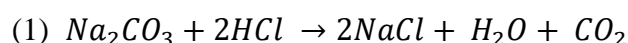
After the reactants were added, the samples were left 20 minutes to ensure that the reaction was complete, then were measured using the RAD7 device, and the results were compared to the activity measured in the absence of other gases in the sample. The

6

144 experiment was conducted for samples with four different radon activities ranging from 23.4

145 $\pm$ 0.9 to 6.7 $\pm$ 0.9 Bq/l. Eight different CO_2 concentrations were used for each radon activity.

146 ### 2.1.2. Hydrogen sulfide experiments

147 H$_2$S was generated in samples with five different radon concentrations ranging from

148 24.6 $\pm$ 1.4 to 6.9 $\pm$ 1.5 Bq/l, while H_2S concentrations used ranged from 0.25 to 3 mg/l.

149 Lower H$_2$S concentrations of 0.125 to 1 mg/l were generated in an additional sample with a

150 radon activity of 10.8 Bq/l, to further study the effect of low H$_2$S concentrations. Hydrogen

151 sulfide was generated by adding ZnS and HCl in the water samples. ZnS was used because

152 the added quantity can be precisely measured, as it is anhydrous. Hydrogen sulfide was

153 formed following the reaction:

154 $$(2) \; ZnS + 2HCl \rightarrow ZnCl_2 + H_2S$$
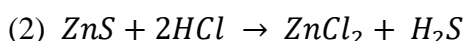
155 All measurements were conducted with an RH% humidity value of under 10% for the

156 RAD7 internal cell, as this is a requirement stated in the DURRIDGE RAD7 user manual. All

157 measured values were subjected to RH% correction, performed by the DURRIDGE

158 CAPTURE RAD7 Data Acquisition and Analysis Software. The device was purged for 20

159 minutes between measurements to exclude any interference on the values from the previous

160 measurement, and also to allow the short-lived decay products of radon to disintegrate to a

161 level that can no longer influence future measurements.

162 ## 3. Results and discussion

163 ### 3.1. LSC and RAD7 radon measurements in spring waters.

164 From the total of 35 spring water samples that were measured, those containing gas

165 displayed a lack of agreement between the LSC and RAD7 radon measured values. However,

166   in the absence of a qualitative analysis of the gas, no clear relationship can be established

167   between the gas content of the sample and the difference in measured activities. The gas

168   content in the samples ranged between 5.7 and 860.0 cm^3/l. The samples that were gas-free

169   showed insignificant differences between values. The difference in radon measured values

170   between LSC and RAD7 had been previously reported in (Stojkovic et. al., 2015). The values

171   obtained using the two methods mentioned above are shown in Figure 1 a) and Figure 1 b).
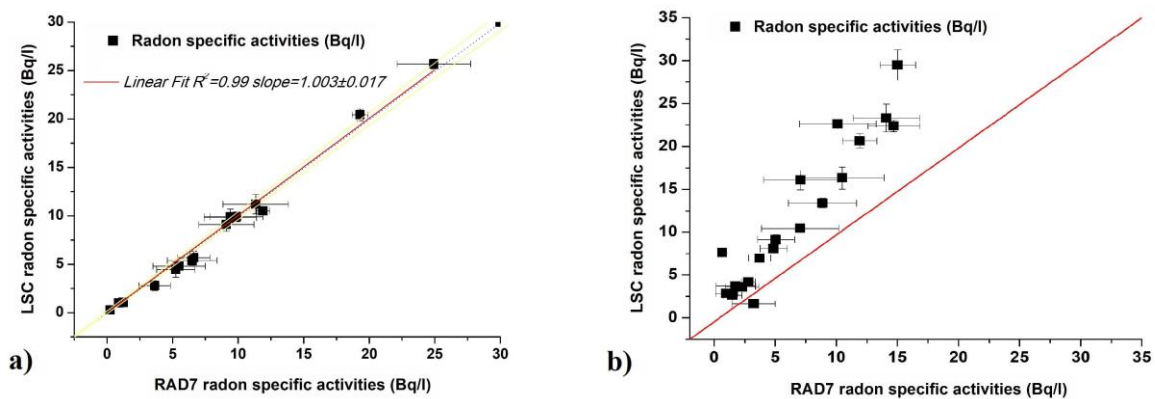
172

173

174   Figure 1. Comparison between LSC and RAD7 radon measured values in natural spring

175   water samples. Panel a) represents the values measured by the two different methods for non-

176   carbonated water samples and panel b) represents the values for carbonated samples. *It can*

177   *be observed that in panel a) the linear fit perfectly overlaps a 1:1 relationship, while in panel*

178   *b there are significant deviations from the y=x function.*

179   **3.2. Influence of carbon dioxide on RAD7 measurements**

180   The apparent radon specific activity displays a decrease with increasing gas (H_2S and

181   CO_2) concentrations, suggesting a reduction in the detection efficiency of the detector.

182   For a low CO_2 concentration of 1.29 g/l, which is commonly found in nature (Komatina,

183   2004), the measured value was 25% lower than the value measured in the absence of added

184   CO_2. A concentration of 3.24 g/l CO_2 led to a decrease of 43% while for a concentration of

CO$_2$ of 5.19 g/l the measured activity was 57% lower than the value registered in the absence of gas (Figure 2 a)).
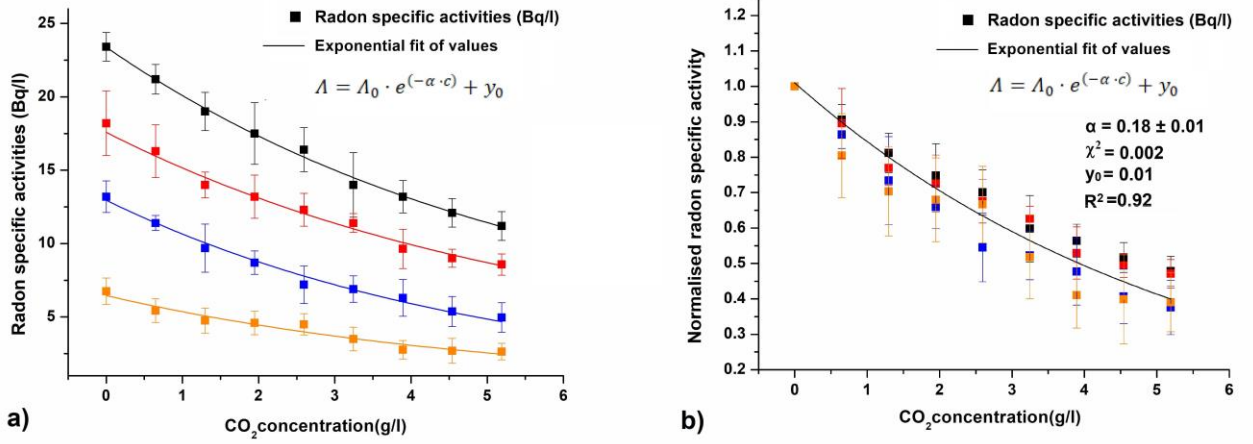

Figure 2. Panel a) represents the dependence of the radon specific activities in water measured by RAD7 in samples with 4 different radon specific activities as function of the concentration of added CO$_2$. Panel b) represents the same values normalized to the specific activity measured in the absence of gas.

An exponential dependency of the measured radon activity values as function of the CO$_2$ concentration can be observed in Figure 2. The data was followed using the following function:

$$(3) \quad \Lambda = \Lambda_0 \cdot e^{(-\alpha \cdot c)} + y_0$$

where:

Λ_0 *is the radon concentration of the sample (Bq/l) measured in the absence of CO$_2$*

c *is the concentration of CO$_2$ (g/l)*

α *is the attenuation coefficient (that describes the loss of detection efficiency)*

y_0 *is a residual detectable activity*

203   The parameters obtained by fitting for radon activities measured in the samples

204   enriched in CO_2 are presented in Table 1. It is important to note that values obtained for the

205   α attenuation coefficient are very similar for all investigated concentrations, the average value

206   obtained being of 0.18 ± 0.01, at a 95% confidence level.

Measured activity in the absence of CO_2	Specific activity in the absence of CO_2 obtained by fitting (Λ_0)	Residual activity (y_0)	α	χ^2	R^2
(Bq/l)	(Bq/l)	(Bq/l)	(l/g)		
23.4±1.0	20.4±1.9	2.9±1.9	0.18±0.03	0.033	0.99
18.2±2.2	15.5±3.0	2.1±0.5	0.17±0.02	0.163	0.97
13.2±1.1	13.0±1.1	0.01±0.1	0.20±0.01	0.066	0.99
6.7±0.9	6.4±0.9	0.06±0.3	0.19±0.03	0.19	0.94

207

208   Table 1. Parameters obtained by exponential fitting (eq.3) of data presented in Figure 2.

209   The interactions of carbon dioxide in soil gas radon measurements were previously

210   studied, including by DURRIDGE company, and a correction factor of 0.3% per 1% CO_2 was

211   suggested to be used for correcting the measured radon values (Lane-Smith and Sims, 2013).

212   Other studies highlighted as well the negative effect of the presence of carbon dioxide on the

213   performance of RAD7 devices in soil gas radon measurements, suggesting that it is not

214   suitable for measurements in CO_2-rich environments without prior separation of carbon

215   dioxide (Shahrokhi et. al., 2015; Tuccimei and Soligo, 2008). The results of the present study

216   show that an exponential dependency between the measured values for [222]Rn in water and the

217   concentration of CO_2 exists. As such, in principle equation 3 can be used for correcting the

218   measured radon specific activity and obtaining the real radon specific activity, if the

219   concentration of CO_2 in the sample is known. The observed behavior can be explained by

220 [218]Po ions neutralization processes that is reducing the electrostatic efficiency of the silicon

221 detector system. After the alpha decay of [222]Rn, [218]Po atoms are produced with 88.2% of

222 [218]Po atoms forming singled charged positive ions in dry air (Wellisch, 1913). Chu and

223 Hopke (1988) note two processes that are leading to [218]Po neutralization: electron-scavenging

224 mechanism and water or gas radiolysis. The polonium atom (ionization potential of 8.43 eV)

225 reacts with oxygen to form an oxide species (PoO_2^+) in dry air atmosphere with an ionization

226 potential in the 10 to 11 eV range (Busigin et al. 1981). This species could then extract

227 electrons from lower ionization potential trace gases such as CO_2.

228   Leung and Phillips (1987) observed that the attenuation coefficient in a pure argon

229 atmosphere is relatively independent of radon concentration for low concentrations but high

230 radon concentrations can influence this value. They suggested that the dominant

231 neutralization process at low concentration is charge transfer, and at high radon

232 concentration, it is ion recombination. Because in normal conditions, the CO_2 molecule is an

233 extremely inactive and stable compound (North, 2015), its behavior in the [218]Po

234 neutralization process is similar to that of argon and argon -nitrogen mixture.

235

236   **3.3. Influence of hydrogen sulfide on RAD7 measurements**

237   The influence of H_2S on RAD7 radon measurements is represented in Figure 3 a) and

238 Figure 3 b). Even for concentrations of H_2S as low as 0.5 mg/l, there is an average decrease

239 of 43% compared to the values measured when no H_2S is present. For a concentration of 1

240 mg/l of H_2S, the measured activities are 66% lower, while for a concentration of 2 mg/l H_2S a

241 decrease of 84% is observed.   Considering that H_2S in groundwater can be present in

242 concentrations of up to 50 mg/l (Komatina, 2004), the underestimation of 84% in the

11

measured radon specific activity observed for a H_2S concentration of 2 mg/l is extremely concerning. An additional experiment was conducted for lower H_2S concentrations ranging from 0.1 to 1 mg/l for a sample with a radon activity of 10.8 ± 0.8 Bq/l for studying the dependence in this lower concentration range in greater detail. Figure 3 a) presents the values obtained for radon specific activities in water samples as function of the different hydrogen sulfide concentrations, with the inset focusing on the low concentration range, while Table 2 presents the results obtained by exponential fitting of the data. It can be observed that for concentrations higher than 3 mg/l of H_2S one is practically unable to perform radon measurements in water using the RAD7 device.
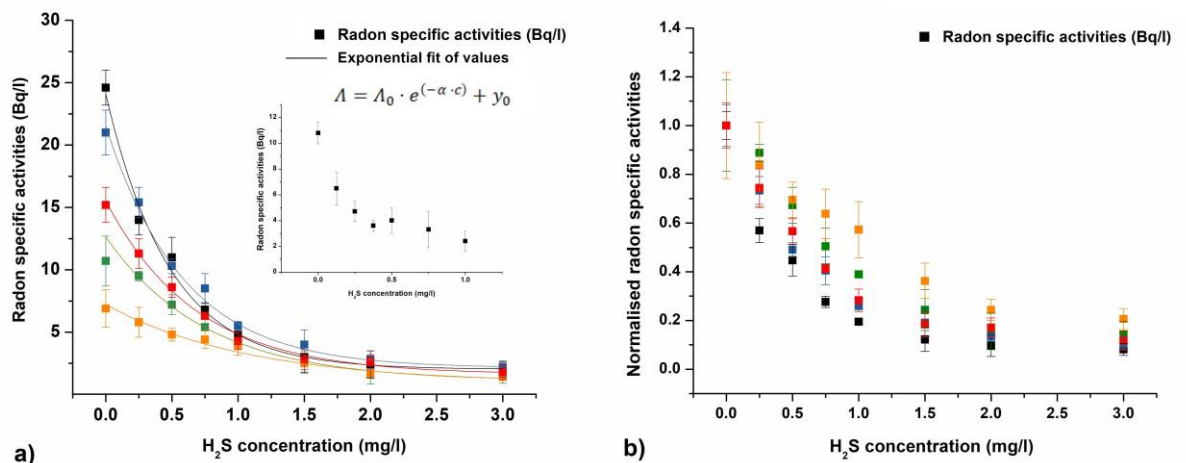

Figure 3. Panel a) represents the dependence of the radon specific activities in water measured by RAD7 in samples with different radon specific activities as function of the concentration of added H_2S. Panel b) represents the same data normalized to the values obtained in the case of no H_2S added.

The dependence can be described by the same exponential equation as in the case of CO_2, in this case the parameter "c" representing the concentration of H_2S expressed in mg/l. The fitting parameters are presented in Table 2. As in the case of CO_2, we attribute the

presence of the residual activity (y_0) to the signal generated by neutralized [218]Po atoms that are reaching the detector surface even if the electric field in the cell has no guiding effect on them.

Measured activity in the absence of H_2S	Specific activity in the absence of H_2S obtained by fitting (Λ_0)	Residual activity (y_0)	α	χ^2	R^2
(Bq/l)	(Bq/l)	(Bq/l)	(l/mg)		
24.6 ± 1.4	22.1 ± 0.7	2.0 ± 0.3	2.07 ± 0.11	0.329	0.99
21 ± 1.8	19.4 ± 0.7	2.1 ± 0.2	1.71 ± 0.09	0.259	0.99
15.2 ± 1.4	13.9 ± 0.6	1.6 ± 0.3	1.47 ± 0.09	0.232	0.99
10.7 ± 2	11.6 ± 0.4	1.1 ± 0.3	1.32 ± 0.10	0.255	0.99
6.9 ± 1.5	6.3 ± 0.4	0.9 ± 0.3	0.93 ± 0.19	0.293	0.96

Table 2. Parameters obtained by exponential fitting (eq.3) of data presented in Figure 3

Unlike in the case of CO_2 enriched samples, for the samples enriched in H_2S the values obtained for the α attenuation coefficient are not similar for different concentrations of radon in the samples, with the values increasing for the samples with higher radon concentrations. The values range from 0.93 ± 0.22 for 24.6 ± 1.4 Bq/l of [222]Rn to 2.08 ± 0.03 for a specific activity of 6.9 ± 1.5 Bq/l of Rn (Figure 4).

13
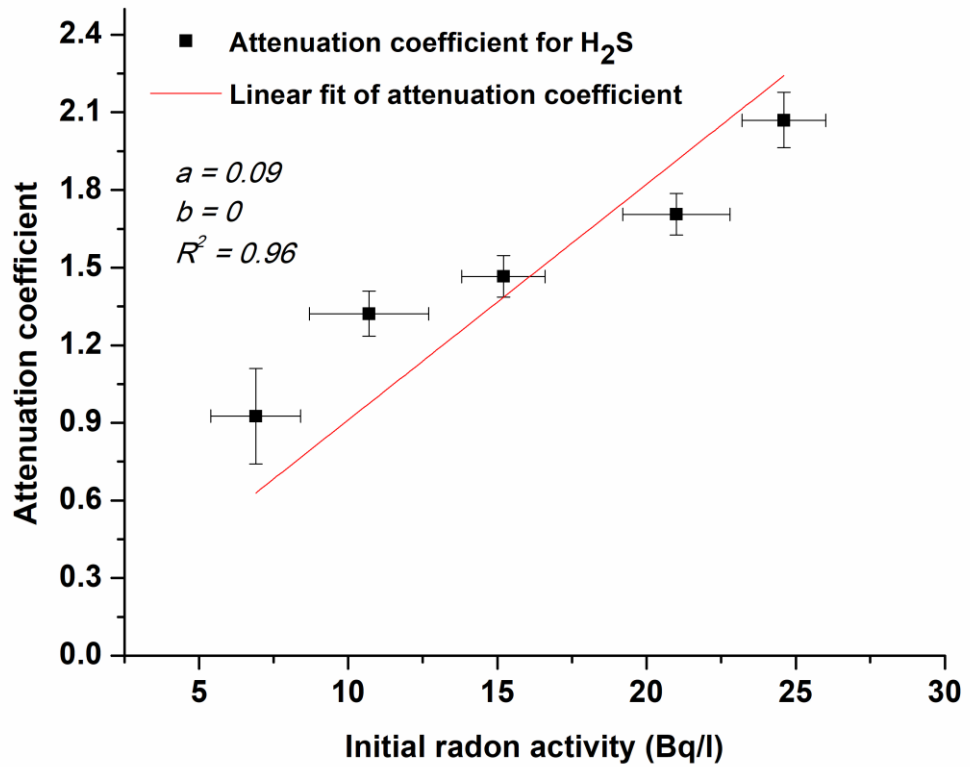
Figure 4. α attenuation coefficient (that describes the loss of detector efficiency) as function of the radon specific activity in the case of samples where the measurements are interfered by the presence of H_2S.

A linear relationship is observed between the attenuation coefficient and the radon concentration and the variation of the apparent radon concentration as function of the H_2S concentration can be written as:

$$(4)\ \Lambda = \Lambda_0 \cdot e^{-(a \cdot \Lambda_0 + b) \cdot c}$$

Neglecting the intercept for simplicity as within uncertainty it is close to zero, the following equation can be applied for performing a mathematical correction of the RAD7 radon measured activities in water samples in which a known concentration of H_2S is present:

14

$$(5)\ \Lambda_0 = -\frac{1}{a \cdot c} \cdot W(-a \cdot c \cdot \Lambda)$$

281

282 *Where:*

283 Λ_0 *and represents the true specific activity of the sample*

284 Λ *represents the apparent (measured) specific activity of the sample*

285 *a represents the slope from the linear fit of the alpha coefficient as function of the radon activity*
286 *reported above*

287 *c represents the H_2S concentration*

288 *W is the Lambert W function*
289

290   Using the value of the slope given above this equation can be applied if the

291 concentration of hydrogen sulfide and the measured radon specific activity in the sample are

292 known, as the values of Lambert W function are tabulated or can be obtained using specific

293 software such as Matlab.

294

295   Many studies show that the counting efficiency is influenced by humidity (Chu and

296 Hopke, 1988; Hopke, 1989; Roca et al., 2004; Simone, 2016). Hopke (1989) highlighted that

297 the ^{218}Po neutralization in the presence of water molecules occurs because of the radiolysis of

298 water, yielding–OH and the hydroxyl radicals, which have an electron affinity of 1.83 eV

299 (Drzaic et al. 1984). The phenomenology behind the observed dependency of the apparent

300 radon activity as function of H_2S concentration can be explain by the similarity of H_2S and

301 H_2O molecules as both are polar molecules that can dissociate, creating negative ions. The

302 radiolysis process described for water is also conceivable for H_2S. The ionization potential of

303 H_2S (10.45 eV) is close to the ionization energy of the PoO_2^+ ion and its proton affinity of 7.7

304 eV. During alpha decays, H_2S can be dissociated into HS^- or S_2^-, the dissociation energy of

305 H_2S (into hydrogen and sulfur) is only 0.2 eV/molecule, compared to water, which has a

306 dissociation energy of 2.9 eV/molecule (Nunnally et al., 2009). Moreover, the water

307 molecules can act as a catalyst and can themself dissociate the H_2S molecule (O'Brien 1991).

308 This can explain the proportionality of the attenuation coefficient with the ionizing radiation

309 activity (Figure 4). These two processes can cause a very strong effect, even at low H_2S

310 concentrations.

311 **3.4. Elimination of CO_2 and H_2S interference on RAD7 radon measurements**

312 As observed from the results of the experiments presented above, the presence of CO_2

313 and H_2S strongly decreases the detection efficiency of the instrument. As such, it is

314 compulsory for correction protocols to be developed and applied for the measurement of

315 radon in natural mineral waters containing gaseous components. Mathematical corrections

316 were presented above, however these corrections rely on having prior information on the type

317 and concentration of the interfering gas. Below we are proposing some experimental

318 procedures that aim at the elimination of the interfering component by chemical precipitation.

319 To test this approach experiments were conducted on a new set of samples collected

320 from the same location in which CO_2 and H_2S were generated following the same procedure

321 described above (section 2.1). For eliminating the interference of carbon dioxide on radon

322 measurements in water, $Ca(OH)_2$ was added in the samples containing CO_2, before the

323 measurement. The added $Ca(OH)_2$ quantity was calculated from the reaction (6), with a 10%

324 surplus. The precipitation of CO_2 as $CaCO_3$ follows the reaction below:

$$(6)\ Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2$$

326 A similar procedure was tested for the water samples with hydrogen sulfide content,

327 by adding $Pb(NO_3)_2$(40 mg of Pb^{2+}) as reactant, for converting H_2S into PbS, that was

328 precipitated and deposited, following the reaction:

329 $$(7)\ Pb(NO_3)_2 + H_2S \rightarrow PbS + 2HNO_3$$
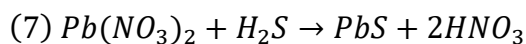
330   Subsequently, after waiting for 20 minutes to ensure that the reaction was complete,

331   the water samples were measured. It was observed that the effect of both gasses was

332   canceled, regardless of their concentration, and the radon measured activity matched the

333   measured activity for sample that were not enriched in CO_2 or H_2S as it can be seen from the

334   data presented in Figure 5 a) and Figure 5 b), respectively.
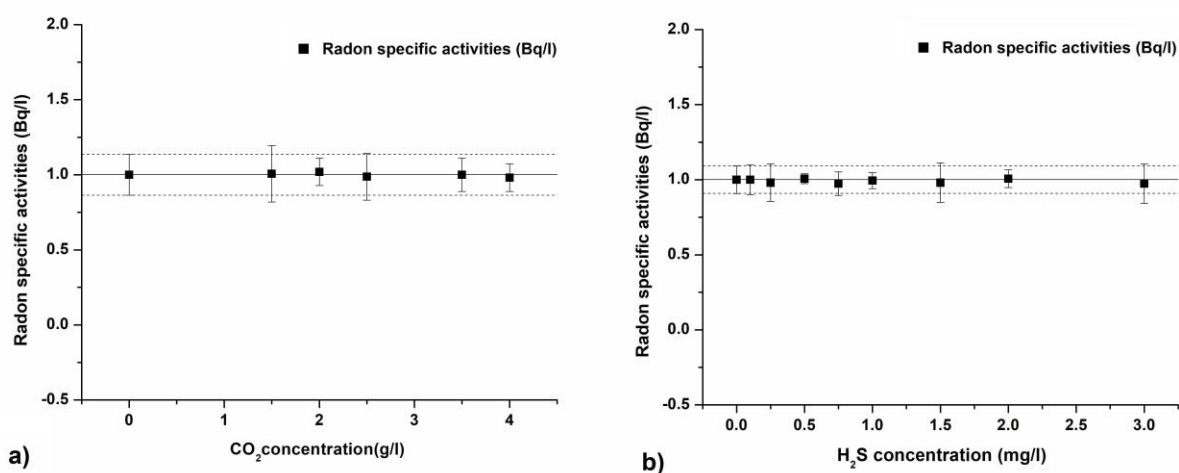

335

336   Figure 5. Specific activities of radon measured in samples where no gases were generated,

337   compared to the values measured in samples in which different concentrations of CO_2 (panel

338   a) and H_2S (panel b) were generated and subsequently neutralized as described above. *All*

339   *values are normalized to the true value of the specific activity (i.e. measured in the absence of*

340   *interfering gases). It can be observed that all vales agree within uncertainties and are*

341   *consistent to unity.*

342   **4. Conclusions**

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In the present study, the effect of the presence of two major gaseous components of natural mineral waters, carbon dioxide and hydrogen sulfide on radon measurements using RAD7 was investigated. For both gases, a decrease of the detection efficiency was reported and an exponential dependence was observed between the apparent activity and the concentration of the interfering gas, suggesting that radon measurements by RAD7 are not accurate when gas-rich waters are analyzed, and a severe underestimation of the true values are expected even in the presence of common concentrations of interfering gases. The findings of the present study are generally applying to all radon measurement devices with electrostatic cells. Mathematical corrections were proposed, however they require independent measurements of CO_2 and H_2S concentrations. A laboratory method based on the precipitation of H_2S with $Pb(NO_3)_2$, resulting in HNO_3 and PbS,, and the precipitation of CO_2 with $Ca(OH)_2$ resulting in $CaCO_3$ and H_2O was proposed. This procedure, if applied before the RAD7 radon measurements, leads to the removal of the effect of carbon dioxide and hydrogen sulfide on the RAD7 radon measured activities.

Considering the results of the present study, it can be assumed that many published articles on radon measurements in water using electrostatic cell radon monitors, performed on samples containing carbon dioxide and hydrogen sulphide, such as carbonated spring waters and hot springs, could present compromised results. The present study serves as a guide for worldwide researchers using electrostatic cell monitors to perform correct measurements on radon in gaseous water samples, as the effect of the investigated gases cannot be overlooked.

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369 **5. References**

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