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Assessment of ambient dose equivalent rate: performance of an automatic survey meter as an instrument to quantify the presence of radiation in soils

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Abstract

Those who work in radiation protection are faced with various quantities that were created to account for the effects of ionizing radiation in the human body. As far as the experimental point of view is concerned, each available equipment is planned to measure a distinct quantity, for a specific radiation protection application, and it is not always clear which one it is. This paper shows a series of tests, planned and applied to a portable gamma ray spectrometer, in order to assure that the monitoring low dose levels of radiation with it is reliable. The equipment is fully automated and does not allow modifications of the conversion factors from counts to ambient dose equivalent. It is therefore necessary to assure that the values provided by the equipment are correct and refer to the actual situation one expects to find in practice. The system is based on an NaI(Tl) scintillation detector, mounted with its electronics in a portable case, suitable for field measurements. It measures ambient dose equivalent rate ($\dot{H}^*(10)$ in $\mathrm{Sv\,h^{-1}}$), total counts in the spectrum (from 50 to 1670 keV) and number of counts per channel (128 channels). The tests presented here are: evaluation of the cosmic component, repeatability, check against standard extended sources, and performance with point sources (^{60}Co or ^{137}Cs) on the ground. The results show that the system can be used, with its built-in conversion coefficients, for in situ measurements, whether or not the ground contains only natural radiation or is additionally contaminated. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

This paper describes the efforts to put into operation a very simple and sensitive unshielded gamma spectrum survey meter, used for low-level field measurements with natural or artificial radioisotopes distributed in the ground. The equipment is commercially available, is sold without any calibration factor, and the manual does not even mention the radiation protection quantity assessed [1]. Furthermore, as remarked by various authors [2,3], the number of quantities and units specific to the radiation protection field leads to

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misunderstandings, difficulties in comparing results and also loss of confidence in the results. Each quantity was defined with a purpose and has certain peculiarities: some are easier to measure or to interpret in a physical sense, whereas others were ideally conceived, making their direct assessment almost impossible. From the experimental point of view, each available instrument is planned to measure a distinct quantity, for a specific radiation protection application, and not always it becomes clear which distinct quantity it is [4,5]. International organizations, like ICRP and ICRU, are attempting to shed light on the field with some recent publications [6,7]. In spite of these efforts, an unwary scientist who begins in this area feels like being literally thrown into a forest of not clearly distinguished quantities. If this confusion happens to an expert, what is to be expected from the manufacturers of instruments? Some of them state proudly in the folders or manuals of modern survey equipment that they furnish their results in Sievert (Sv). But which "Sievert" is that? Unfortunately, the same special unit is used for effective dose (sum of absorbed doses in tissues and organs, doubly weighted: for all radiation types and for all tissues and organs of the body), dose equivalent and effective dose equivalent (still in use, despite the fact that they were superseded in 1991 [8]), and equivalent dose, ambient dose equivalent, personal dose equivalent, directional dose equivalent [6]. Most of the time, what happens is that the "Sievert" shown by the apparatus is not related to any of the above-quoted radiation protection quantities but is the result of a mere conversion of units from exposure (in Roentgen) to "something" in Sv, using 1 Sv $\Leftrightarrow$ 100 R. Thus, the tests performed with this survey meter, described here, were necessary to guarantee that the measured quantity is the operational quantity "ambient dose equivalent $H^*(10)$" [6] and that the measured values are correct within the experimental uncertainties. Although in Brazil there is no legal requirement, nor habit, of doing calibration of environmental detectors in conditions similar to the field measurement, it is important to have the responsibility of carrying out this task so that the obtained results are reliable.

2. Experimental details

The instrument in test (Hamamatsu Photonics Spectrum Surveyor Model C3475) is portable (1.0 kg, powered by alkaline batteries) and has a cylindrical (25 mm diameter, 50 mm height) NaI(Tl) scintillation crystal, coupled to the usual electronics. A 128 multichannel analyzer furnishes the spectrum, visualized in real time in a liquid crystal screen, from 50 to 1670 keV (13 keV/channel) and assessed by computer via an RS232 interface. The time interval of measurement can be chosen from 30 s to 24 h. The measuring quantities are ambient dose equivalent rate and counts or count rate (per channel or total). It is also possible to integrate manually any portion of the spectrum or automatically the photopeaks of some known isotopes (fixed windows for ^{141}Ce, ^{131}I, ^{103}Ru, ^{137}Cs, ^{60}Co, ^{40}K). Some calculations like sum and subtraction of spectra can also be done. Minor adjustments in the high voltage are possible, to compensate for temperature drifts or changes in electronics, checked with a suitable ^{40}K source.

The sources used in this work were: small point sources of negligible size either of ^{60}Co (12 sources with low activities $\sim$1 μCi or 0.04 MBq), or of ^{137}Cs (one source with medium activity: 0.12 mCi or 4.4 MBq) and extended sources of natural radioisotopes. These extended sources have a mixture of known quantities of natural potassium, thorium and uranium minerals, assumed in secular equilibrium with the whole daughter series, in concrete pads with 3.0 m of diameter [9].

Although, due to the small size, the detector is inefficient in detecting high-energy cosmic radiation, there is a contribution from it in the measurement that has to be evaluated, in order to obtain the actual gamma radiation dose, by subtracting that part. The cosmic component is to be estimated at a place, where the gamma rays from the soil do not enter the detector, but at the same longitude, latitude and altitude of the rest of the experiments. This was performed inside an aluminum boat floating on a dam with clean water (more than 10 m depth and more than 10 m in the lateral dimension), in the city of São Paulo (altitude 800 m, latitude 23.4 S, longitude −46.7). The influence of the boat itself on the

measurement is negligible, as its mass is small and the detector has a wide solid angle (approaching 2π steradian with this arrangement). The water acts as a shielding to the gamma rays originated from the soil (to illustrate, a 10 m water layer attenuates a 1.5 MeV beam of photons by a factor 10^{11} [10]) and is almost exempt of radioisotopes solved in it [11].

3. Results and discussion

3.1. Assessment of the cosmic component

The spectrum obtained with the detector inside the boat is shown in Fig. 1, together with another taken at 1 m height from the ground. The gross ambient dose equivalent rates recorded by the survey meter in both the situations are, respectively, 25.7 and 107 nSv h^{-1}. The value 25.7 nSv h^{-1} was adopted for the cosmic contribution, although it should not be confused with the cosmic component of the dose, as the detector is not designed nor suitable to measure it. There are also experimental limitations in the measurement: gamma rays from radioisotopes in the atmosphere may be included, and, as the lateral dimensions of the water dam are limited, part of the gamma rays originated in the soil may reach the detector, either directly or after scattering in air.

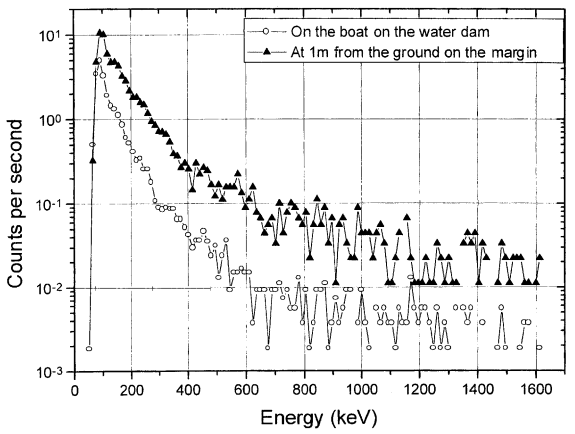

Fig. 1. Spectra obtained over a great mass of water to evaluate the cosmic contribution to the measured spectra (○) and at the margin of the water dam (▲) for comparison.

Only one set of measurements was performed outside the city of São Paulo: the tests with planar sources, achieved at Rio de Janeiro (altitude 1 m, latitude 22.9 S, longitude −43.2). As it was not possible to obtain the local cosmic ray contribution, a correction for the altitude variation was done in the São Paulo data. According to Bayley's data [12], that show equivalent dose rate as a function of altitude, it was possible to infer the cosmic contribution in Rio de Janeiro as 18 nSv h^{-1}. The minor longitude and latitude corrections were neglected.

3.2. Repeatability

With the detector in a fixed position, a large number of measurements of short integration time (120 s) was carried out, for evaluating the fluctuations in the ambient dose equivalent rate and in the total counts. The uncertainty observed in these circumstances is related to the emission of radiation and to the detection process itself (detector plus electronics). The total count and dose rate distributions are both approximately symmetric, as can be seen by the histograms and the fitted Gaussian curves in Fig. 2. The distribution of total count values, resulted in a standard deviation $\sigma = 174$ counts, 20% larger than the $\sqrt{20,639} = 144$ counts expected by Poisson statistics. Regarding the ambient dose equivalent rate values, the standard deviation represents 1.4% of the mean value. Therefore, this value was used as the minimum uncertainty of one measurement, as it reflects the fluctuation due to the equipment.

3.3. Check against standard extended sources

The calibration of a portable dosimeter should be performed, if possible, at the same conditions it is to be used. This task is not easy to achieve, as a plane source with infinite dimensions and known amounts of gamma emitters is not feasible. Usually, the solution is provided by large dimension sources, with known homogeneous distribution of natural radionuclides to simulate the actual field conditions.

In Brazil (at Instituto de Radioproteção e Dosimetria—Rio de Janeiro), there is a set of

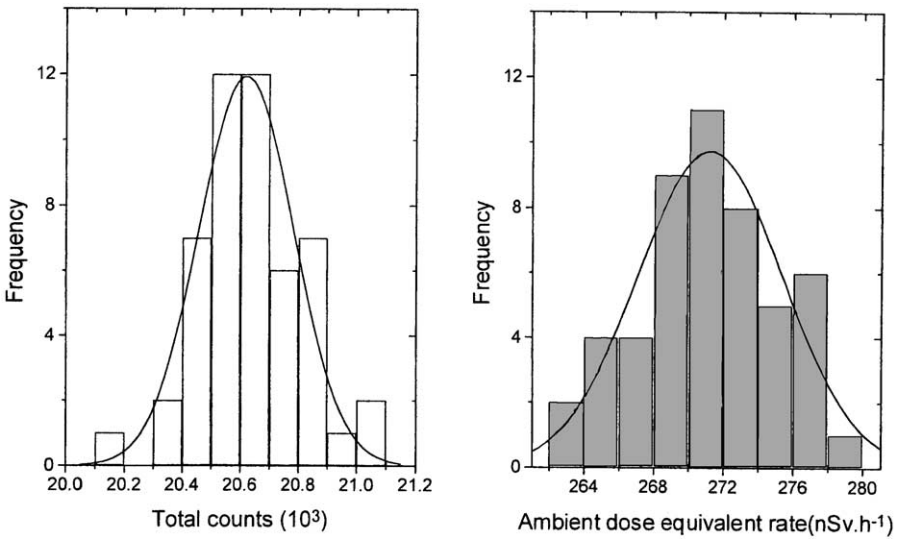

Fig. 2. Histograms of total counts (left) and ambient dose equivalent rate (right) obtained with the detector at a fixed position. Each graphic contains 50 measurements of indoor background integrated over 120 s. The curves are Gaussian fitted to the data.

Table 1
Identification of the planar sources with natural isotopes used to calibrate the detector

Source identification	K content (%)	Nat U content (ppm)	^{232}Th content (ppm)
K1	6.71(6)	2.00(7)	20.90(81)
K2	4.43(8)	2.97(6)	29.7(14)
U1	3.47(4)	69.92(67)	50.13(99)
U2	3.43(7)	19.45(14)	53.1(17)
UTh1	3.64(3)	12.10(24)	71.6(18)
UTh2	3.65(3)	44.47(63)	152.4(48)
Th1	3.54(7)	11.63(15)	256.0(52)

The furnished concentrations were obtained by neutron activation and chemical analysis [9].

such sources, whose uranium, thorium and potassium contents are described in Table 1 [9]. The sources are cylindrical, 3.0 m diameter, 0.50 m height, made of concrete mixed with minerals containing known amounts of natural radionuclides. They are placed on the soil, at sea level, their centers forming a circle with 10 m radius, hence the distance between the borders of each pair of pads is approx 5 m. Because of the finite source dimensions, the recommendation is to place the detectors in contact with the source surface, instead of the usual position, i.e. 1 m above the ground. Therefore, the influence of the surrounding regions that have different amounts of gamma emitters is lessened by the solid angle modification. To exemplify, the net $H^*(10)$ in the field neighboring the experimental setup was determined as $40\,\mathrm{nSv\,h^{-1}}$.

In Table 2, the results obtained in this work are presented and compared to other experimental findings [9,13] and to the classical calculation, that uses adequate conversion factors recommended by ICRU [14] (in this case, the uncertainties presented derive from the uncertainties in the radionuclide contents). For an appropriate comparison, the values of $H^*(10)$, after subtraction of the cosmic

Table 2
Ambient dose equivalent and air kerma rates for the extended sources described in Table 1

Source	Measured $H^*(10)$ (nSv h^{-1})	$\dot{K}_{air}$ (nGy h^{-1})			
		This work	Barreto [9]	Conti [13]	ICRU-53
K1	169(5)	109(4)	113(5)	114(1)	152.2(22)
K2	180(5)	116(4)	109(6)	121(1)	149.6(36)
U1	464(14)	321(10)	324(17)	322(2)	589.3(47)
U2	278(8)	188(6)	184(7)	193(2)	292.9(43)
UTh1	304(8)	206(7)	208(9)	213(2)	297.2(46)
Uth2	650(20)	455(14)	446(23)	445(2)	691(12)
Th1	740(22)	520(16)	534(28)	518(3)	747(13)

Column 2 shows the data obtained with the Hamamatsu gamma ray monitor; column 3 shows the column 2 values converted to kerma rate in air ($\dot{K}_{air}$) using the average factor 0.72 Gy Sv^{-1} obtained from Table A21 of Ref. [6], after subtraction of the cosmic contribution; in columns 4 and 5 the $\dot{K}_{air}$ values obtained by other researchers [9,13], in the same experimental conditions; the last column shows $\dot{K}_{air}$ values calculated using the coefficients suggested by ICRU-53 [14] to convert specific activity to kerma rates at 1 m from the ground for infinite sources.

contribution, were converted to kerma rate in air, that is the quantity chosen by the other authors. The conversion factor used, as the actual gamma ray spectra are not known, was taken as an average of the proposed values of Table A21 in ICRP 74 [6], in the energy region of the detector sensitivity, namely 1.39 Sv Gy^{-1}. As can be seen in Table 2, the three sets of experimental results are in good agreement among them, but not with the calculated values. The discrepancy is large, since the experimental kerma rate values are, on average, only about 70% of the calculated ones. In order to explain this discordance, it is important to verify if the assumptions of the experimental and theoretical methods are similar. The chief hypothesis of the calculus suggested by ICRU [14] are Refs. [15–17]: the source has infinite thickness and area, consists of homogeneous soil with known amounts of the uranium and thorium radionuclide series, in radioactive secular equilibrium, in combination with natural potassium, all of them uniformly distributed in the whole volume.

The initial tests performed with the pads [9] indicated that the radionuclides were uniformly distributed in the volume and that the concrete matrix was homogeneous throughout all of the pads; besides that, the radioactive equilibrium attainment was also verified; moreover, the constancy of the kerma rates (see Table 2) in a period of 13 years shows that the climatic conditions did not significantly damage the pads.

Chen [18] and Kim et al. [19] estimated the influence of the source dimensions on kerma rate values with Monte Carlo calculations performed with sources of finite thickness and finite radius, respectively. According to Chen's studies, the effective dose equivalent values 1 m above the ground become nearly constant for sources of thickness higher than two or three photon mean-free-path (mfp) lengths in the soil. As the highest gamma ray energy emitted by natural radionuclides [20] is 2.615 MeV (from ^{208}Tl—36% of the decay rate of ^{232}Th in secular equilibrium), whose mfp length in the soil is around 25 cm [18], we can conclude that the thickness selected to manufacture the sources (50 cm of concrete) is satisfactory.

On the other hand, there is a strong possibility that the hypothesis of infinite surface is not fulfilled: as shown by Kim [19], an extremely thin 1 MeV gamma ray source increases the kerma tissue rate at 1 m from the ground, directly over its center, by 43% in case its radius is augmented from 2.0 to 3.0 m. Although these figures must be regarded with prudence, as the actual conditions are very different from the calculation scenario (for instance, the concrete sources have a finite thickness, the surroundings are not radiation-free as assumed by the authors in the calculation, and

the detector was in contact with the concrete pad and not 1 m above it), they corroborate the judgment that the finite radius of the source is the most relevant factor to account for the discrepancy between theoretical and experimental values.

3.4. Performance with point sources

The good sensitivity of the detector was verified with the use of low activity ^{60}Co sources. One source with around 40 kBq ($\sim$1 μCi), placed at 1 m distance from the detector increases the background signal (268 nSv h^{-1}) in 23.5 nSv h^{-1} (more than five times the respective uncertainty), albeit the cobalt photopeaks are not salient from the background spectrum.

Another important test is related to the coherence of the system response with the position of the source. This was done to experimentally simulate the presence of a contamination spot (or a set of spots) in an otherwise homogeneous infinite source as the soil or the floor of a laboratory. The experiment consisted in dispersing a variable (1–12) number of sealed sources of comparable activities on the ground, at known distances from the detector, and measure $H^*(10)$. For each situation, the expected contribution from the set of sources was also calculated based on the knowledge of the contribution of one source at a distance of 1 m from the detector. The assumptions of the calculation were: dose varies with the inverse square of the distance (between 0.70 and 2.50 m), all the cobalt sources have the same activity and all the individual source contributions are simply summed. The ratios of the measured to the calculated values are shown in Fig. 3: the points that refer to cobalt were obtained using 1, 2 or 12 similar sources (quantity shown in the labels), whereas the points obtained for ^{137}Cs source were taken always with one sole source. The large error bars in the cobalt points, compared to the cesium ones, are due to the smaller values of $H^*(10)$ as the sources have very low activities. The approximate constancy of the relation between the measured and expected values indicates that the detection system performs well in the presence of contaminated surfaces, even when they are

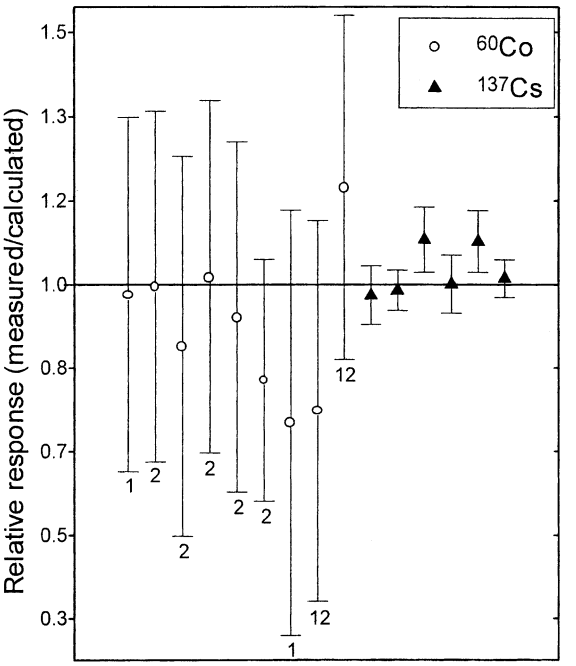

Fig. 3. Ratio of measured and calculated values (based on the measurement with one source at 1 m from the detector) of ambient dose equivalent rate, obtained with ^{60}Co (○) and ^{137}Cs (▲) point sources distributed in a plane below the detector. The labels in the points corresponding to ^{60}Co refers to the number of similar sources used in the measurement.

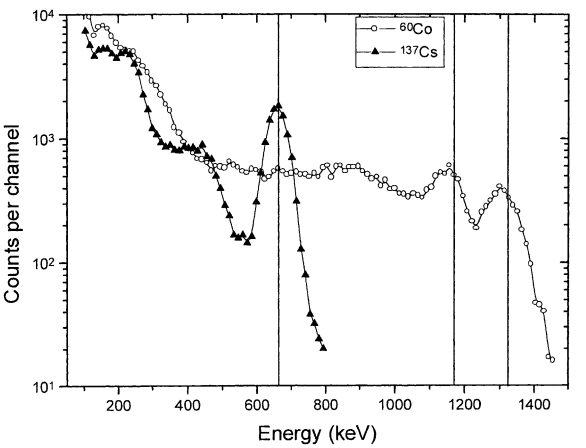

Fig. 4. Net spectra obtained with 12 ^{60}Co ($\sim$40 kBq each) at a distance of 1 m from the detector (○) integrating within 30 min, and one ^{137}Cs source with around 4.4 MBq (▲), also at a distance of 1 m from the detector, integrating within 3 min. The vertical lines indicate the expected positions of the 3 photopeaks.

very small in size, as hot spots, and give little contribution to the dose.

3.5. Source identification

Fig. 4 shows two spectra obtained with the setup described earlier, after subtraction of the background contribution. One of the spectra refers to the 12 ^{60}Co sources placed together at a distance of 1.0 m from the detector and the other one to the ^{137}Cs source in the same position. As can be noticed, the peaks corresponding to the gamma emissions are easily identified. In fact, when the contribution of the point sources is equivalent to about 50% of the background signal, the photopeaks are always visible. Of course, the intrinsic poor resolution of the detector hinders the exact identification of sources in general. Nevertheless, as far as radiation protection applications are concerned, a good efficiency is more important than a strong resolution.

4. Conclusions

The gamma rays emitted by natural sources have energies in a very wide range. Although the Hamamatsu detector does not take into account the high energies region (above 1.67 MeV), it passed the test with the natural extended sources and small artificial sources. It is important to keep in mind the fact that the contribution of the higher energy gamma rays to the dose is primarily by means of scattering and this part is included in the measured spectra.

The equipment showed good accuracy and precision in the tests performed: in terms of ambient dose equivalent rate, the repeatability is 1.4% of the mean, and the measured values in extended sources are coincident with the expected ones, within the uncertainty limits.

The good sensitivity of the detector was verified with the use of low activity ^{60}Co point sources, showing that it measures the contribution of a $\sim$1 μCi source at a distance of 1 m. Also, the observed variation of response according to the position of the point sources indicates that the detection system performs well in the presence of contamination. In fact, recently a research was conducted in the city of Goiânia using this system and other techniques (as spectroscopy of soil samples and thermoluminescence) to evaluate the situation 12 years after the radioactive accident with a therapy cesium source, and the results were consistent [21].

The photopeak corresponding to a gamma source become detectable whenever the source contribution to the signal is equivalent to about 50% of the remainder of the spectrum. The limitation for the identification of the radioisotope is, of course, the intrinsic poor resolution of the NaI detector. This trade-off between efficiency and resolution, as far as radiation protection applications are concerned, is not a problem. Certainly, the use of this system in quantitative assays of other nature requires the knowledge of the absolute efficiency of the detector.

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