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Scintillation Spectra From Point Sources in a Scattering Medium[1]

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In 1958, Rundo (1) suggested that changes in scintillation spectra might be used as a method of determining the depth of a point source in a human body. Over a number of years, experiments have been carried out in this laboratory to examine the shape of scintillation spectra from thick sources with particular application to the effects observed in the counting of humans in a whole body counter ("steel room"). The present paper reports results particularly pertinent to the estimation of the depths of point sources of gamma radiation in a human body using only a single sodium iodide crystal. It is clear that the location of sources is more straightforward if scanning of the body in both horizontal and vertical planes is carried out. However, at the present time there are many laboratories where single detector whole body counters exist without scanning facilities (2).

The most noticeable effects of the scattering of originally monoenergetic radiation on the shapes of the scintillation spectra observed are a widening of the photopeak, a filling of the gap between the photopeak and the Compton plateau, and a build-up of low energy pulses. Of these three, the second is the most valuable for characterizing the changes that occur (3,4); the valley-to-peak ratio, V/P, defined as the number of counts in the lowest channel between the photopeak and the Compton plateau divided by the maximum count in the photopeak, is a useful parameter for describing this effect.

This valley-to-peak ratio, and the change in apparent resolution are used in the present paper to measure changes in the shapes of spectra obtained from gamma ray sources of energies from 0.28 to 1.53 MeV when they are at different positions in a water phantom simulating the human body.

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APPARATUS AND EXPERIMENTAL PROCEDURE

In order to obtain differential energy spectra of a source immersed in water, NaI (Tl) crystals and a hundred channel pulse height analyser were used. Three separate crystals were employed in order to test the consistency of the results obtained.

Figure 1 is a schematic diagram of the apparatus. Water was in a ¼ inch thick plexiglass container 41 cm × 34 cm and 44 cm high. This box was put 7 cm above the floor of the University of Toronto low activity steel room (5). A separate ¼ inch plexiglass support fitted inside this container to hold the sources which were, themselves, contained in glass bulbs varying in diameter from 1.5 cm to 2.0 cm. The strength of the sources was normally between 5 and 15μC, comparable to the maximum permissible radioactive body burden for humans for many isotopes. Sources of ^{203}Hg, ^{51}Cr, ^{85}Sr, ^{137}Cs, ^{58}Co, ^{65}Zn, ^{47}Ca, and ^{42}K with photon energies of 0.28, 0.32, 0.51, 0.66, 0.81, 1.11, 1.31, and 1.53 MeV, respectively were used.

A large number of possibilities exist for the arranging of the various parameters D (the depth of the source in the water) and S, the distance of the surface of the liquid to the NaI crystal. In all the present experiments the values of S and D have been kept at values that might well be experienced in counting

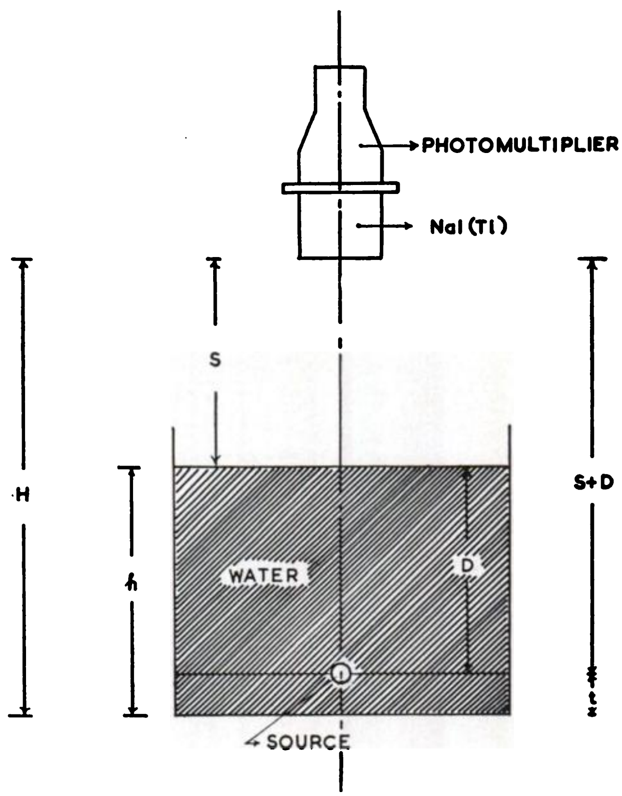

Fig. 1. A diagram of the experimental arrangement, showing the relative positions of source, scatterer and detector.

with a single crystal, with the phantom replaced by a human. Furthermore, in the present series of experiments, S + D was kept constant, but the total depth of water, h, varied, and, therefore, D varied. This corresponds to the counting in a standard geometry of persons of various thickness or obesity. This paper also presents results obtained when persons of varying weight lay on sources, in which cases also S + D remained constant, but D varied. In all cases, the source was on the extension of the detector crystal axis.

The main experimental procedure then consisted of measuring scintillation spectra as the level of water in the container was raised in 1 or 2 cm steps to a maximum of 32 cm (of which 4 cm was below the source), and then repeating the procedure for different sources. Subsequently, the data were analyzed to compute the apparent resolutions that is, the full width of the photopeak at half height $\triangle$E, divided by the energy of the photopeak E.

RESULTS AND DISCUSSIONS

In the first part of this section the valley-to-peak ratios will be discussed, and in the second, the effects on resolutions. In both cases the source–detector geometry (S + D) is kept constant. The third section contains the results of work to test specifically the applicability of the technique to locating sources in humans.

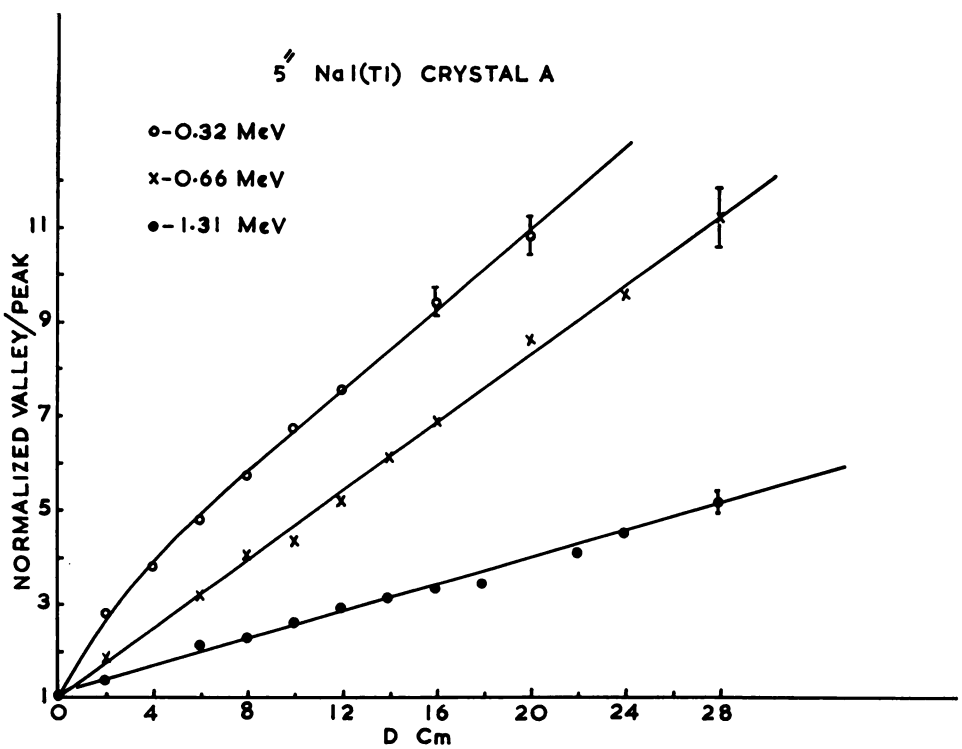

Fig. 2. Normalized valley-to-peak ratios for the spectra obtained from a 5 inch NaI crystal for sources of different energy as the depth of water above the source is altered, the source-detector geometry being kept constant.

(a) Valley-to-peak ratio

Figures 2 and 3 are graphs of the normalized valley-to-peak ratios for two of the crystals used. The normalized ratio $(V/P)_n$ is the value $(V/P)_D$, the ratio with the source at depth D, divided by $(V/P)_o$, the ratio at zero depth of the source. To avoid confusion on these graphs, and on Fig. 4, only a few of the curves obtained have been shown. In none of the cases were there variations from the trends indicated.

Particularly for the higher gamma ray energies, the variation of $(V/P)_n$ with depth is nearly linear, so that it is possible to write $(V/P)_n = a + bD$, with approximate unity. Both b and the value of $(V/P)_o$ are functions of the crystals used and the gamma ray energy.

The results may be discussed in terms of build-up factors (6). In "poor geometry", the exponential absorption law can be modified to $I_D = I_0 B_D \, e^{-\mu D}$ where B_D is the build-up factor corresponding to a particular absorber or scatterer thickness D and to a particular photon energy. Subtracting the unmodified primary contribution, the scattered radiation contribution is $I_0 e^{-\mu D}(B_D - 1)$. In the scintillation spectrum observed, the count in the valley region is composed of some fraction g of the primary radiation and a fraction g′ of the scattered radiation, *i.e.*, $V = gI_0e^{-\mu D} + g'I_0e^{-\mu D}(B_D - 1)$. To a first approximation, the

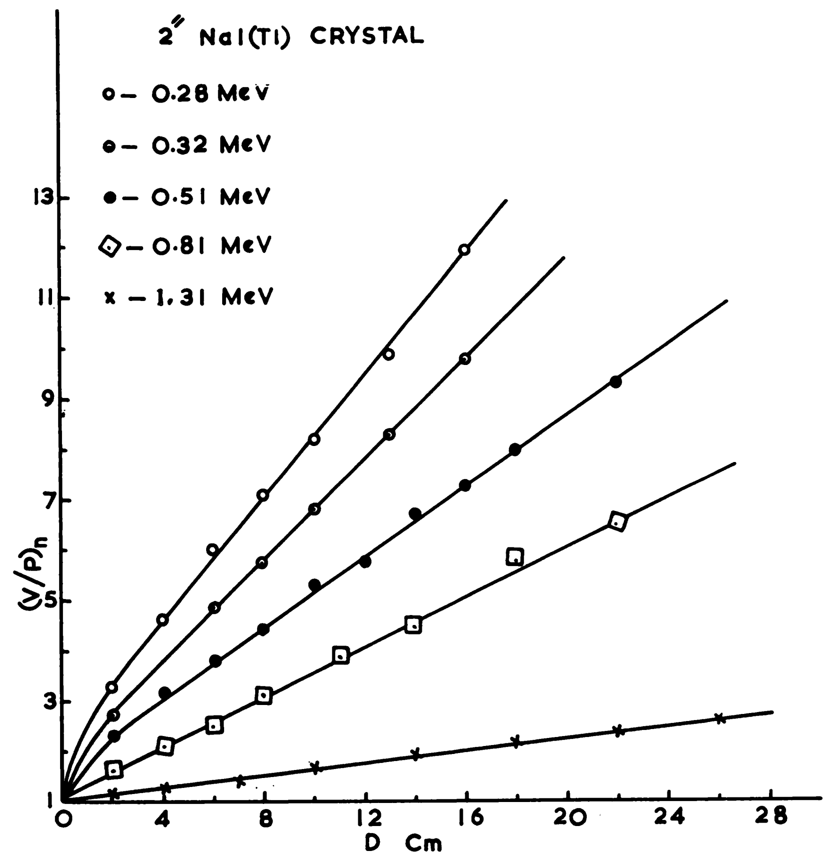

Fig. 3. Normalized valley-to-peak ratios for a 2 inch NaI crystal.

count in the photopeak, P, will, however, be proportional only to the number of photons which did not suffer interaction, that is, $P \propto I_0 e^{-\mu D}$. Then $(V/P)_D/(V/P)_o = [g + g'(B_D - 1)] / g$, remembering that $B_o = 1$. Simplifying, and putting $B_D \approx 1 + mD$, where m is proportional to the absorption coefficient (6), $(V/P)_D / (V/P)_o \approx 1 + \frac{mg'}{g} D$, which is the form found experimentally. More correctly, the photopeak will receive other contributions than the primary radiation alone. The effect of photons which have suffered only a very small angle collision will be small, as will be seen, for the changes in apparent resolution are small when compared with changes in valley-to-peak ratios. Random coincidences between photons which individually would only have given rise to Compton pulses could also contribute to the photopeak, but here the micro second resolving times and the counting rates involved make this effect negligible.

Rundo (1) measured the peak-to-valley ratio for a 0.66 MeV source in a water phantom for thicknesses up to 10 cm, the source-detector geometry being kept constant. This ratio (the inverse of the one used here) does not give a straight line with depth, but converting the results to valley-to-peak ratios does give an approximately linear relationship with depth, in agreement with the present work.

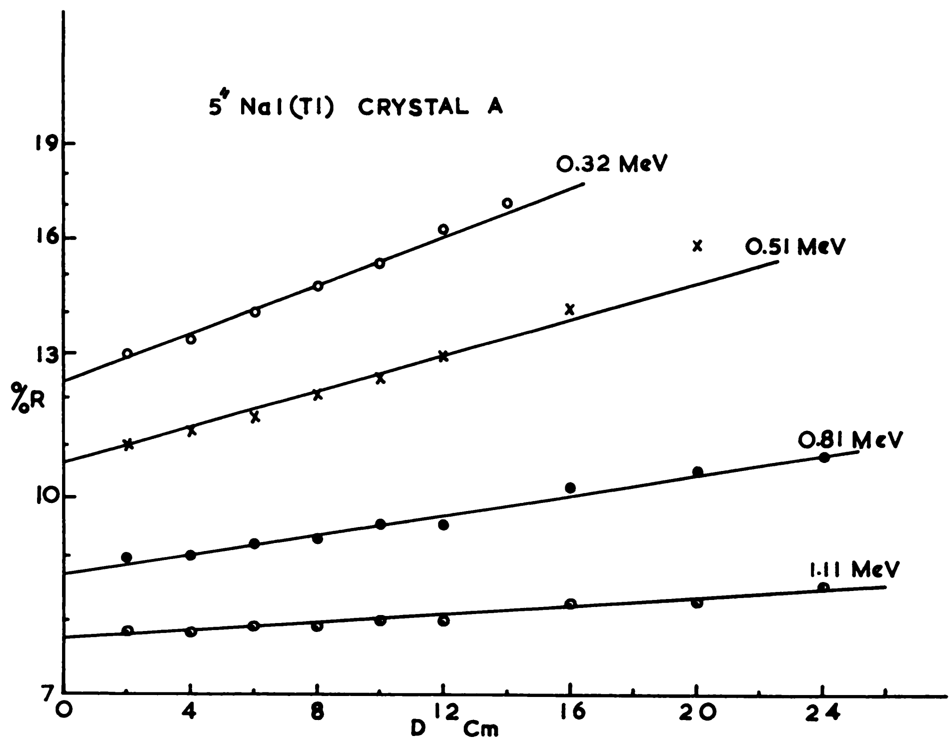

Fig. 4. The variation with source depth D of the log of the apparent resolution ($R = 100 \triangle E/E\%$) obtained with an amount of scatterer D above the source (source-detector geometry constant).

(b) Resolution

As stated above, previous work (3) with distributed sources suggested that the changes in apparent resolution caused by scattering are not as useful for characterizing the effects of scattering as is the valley-to-peak ratio. The present work with point sources confirms this. Figure 4 shows that the normalized resolution (the apparent resolution for a given depth divided by the resolution obtained with a point source, $R_n = R_D/R_0$) varies exponentially with source depth, but the changes in resolution are relatively small compared to the changes in valley-to-peak ratio. The present work has been carried out with sources which are predominantly monochromatic. For convenience with nonmonoenergetic sources, the highest gamma ray should be used to avoid complications arising from the increase in low energy photons that scattering produces (3). Results, similar to those presented here, should not be affected by gamma rays whose energy is well below (*i.e.*, taking into consideration the effect of resolution) the Compton edge of the spectrum.

(c) Work with Humans

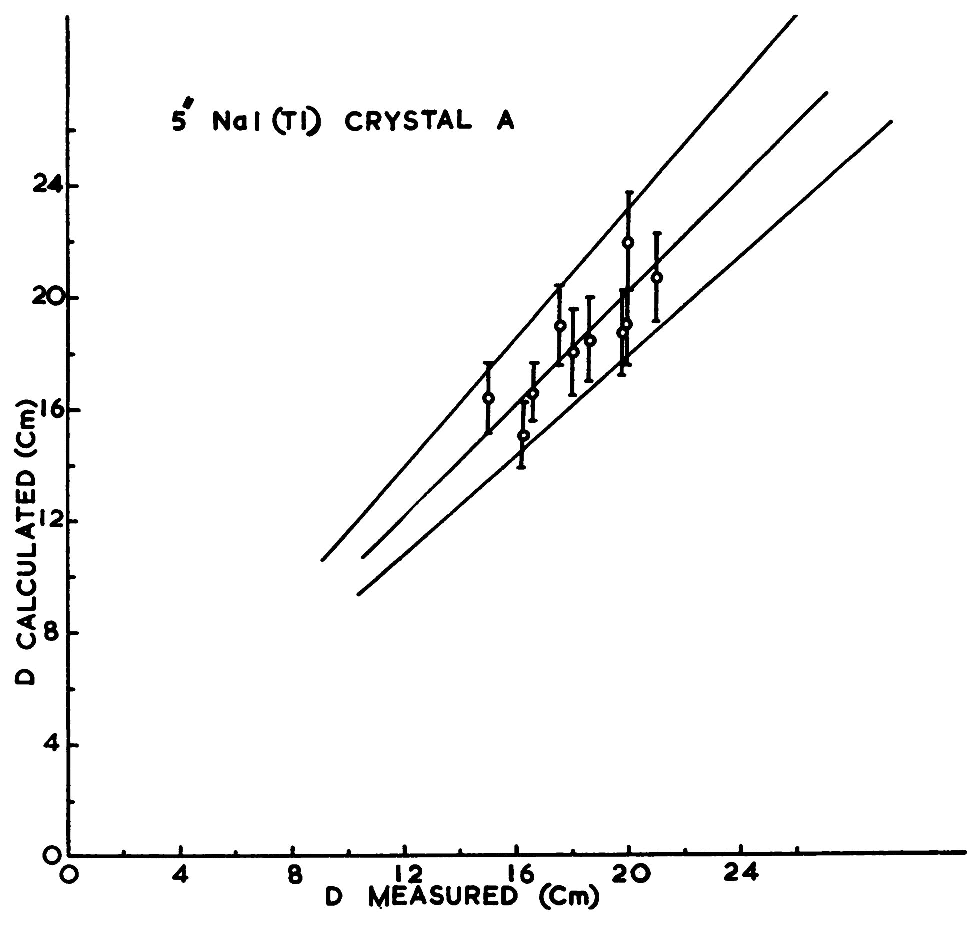

Fig. 5. A comparison of the thicknesses of 12 individuals measured with calipers (D measured) and the thicknesses calculated from the valley-to-peak ratios found when a source was placed below their backs (D calculated).

The fact that relatively simple relationships exist between D and the characteristics of the scintillation spectra suggest that in certain cases the shapes may be used to give information on source depth. As a test of the applicability of the work reported above, the thickness of a person was measured using a single 5 inch NaI crystal and a point source of gamma radiation placed immediately beneath the subject's back. This test was carried out on 12 male subjects of different size. The results obtained by this method, using the change in valley-to-peak ratio as a measure of source depth below the surface of the body, are plotted in Fig. 5 against the body thickness (chest to back) measured with calipers.

The results indicate that a first approximation to the source depth can be obtained by this method; but the spread in results suggests that individual variations, which will include such things as the relative sizes of lung cavity, make determinations with an accuracy better than 10 or 15 percent unlikely in any individual case. Moreover, the variations that occur from one crystal to another (Figs. 2 and 3) imply that a full calibration of the particular system used would have to be carried out. Although these tests have been made with values of D of greater than 14 cm, the agreement with the phantom results strongly suggests that the method would be valid for smaller thicknesses.

All these measurements have been carried out with point sources, but similar kinds of results are obtained with distributed sources. The two cases may, in fact, be differentiated by comparison of the relative changes in the valley-to-peak ratios and the apparent resolutions (7), but the situation is certainly complicated if it is not known whether the source is discrete or distributed.

To summarize, it may be concluded that simple relationships exist between suitably chosen parameters describing the shape of scintillation spectra and the depth of a point source in a scattering medium; and that, after calibration, it would be possible to use the method to make a rough estimate of the depth of a point source in a human body.

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REFERENCES

1. RUNDO, J.: Body Radioactivity Measurement as an Aid in Assessing Contamination by Radionuclides. Paper P/1467, Vol. *23*, p. 101, 2nd Geneva Conf. on Peaceful Uses of Atomic Energy, 1958.

2. Directory of Whole Body Radioactivity Monitors, IAEA, Vienna, 1964.

3. MCNEILL, K. G. AND GREEN, R. M.: Scintillation Spectra from Thick Sources. *Can. J. Phys.* 39:1842, 1961.

4. MCNEILL, K. G. AND MOHINDRA, V. K.: Shapes of Scintillation Spectra. *Assessment of Radioactivity in man.* IAEA, Vienna, 1:79-86, 1964.

5. MCNEILL, K. G. AND GREEN, R. M.: Measurements with a Whole Body Counter. *Can. J. Phys.* 37:683, 1959.

6. MURRAY, R. L.: Introduction to Nuclear Engineering, (2nd Ed.), Prentice Hall, Englewood Cliffs, N. J. Pp. 254-267, 1961.

7. MOHINDRA, V. K.: Ph.D. Thesis, University of Toronto, 1964.