Development of a Dosimetric System using Spectrometric Technique suitable for Operational Radiation Dose Measurements and Evaluation

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1. INTRODUCTION
Recently, the radiation quantities and units of radiation and measurements have rapidly progressed in the radiation protection fields, corresponding to the concept reflecting the radiation sensitivity and effects to human body. According to this progress, the measuring system of radiation dose is rapidly advancing in the radiation protection fields. Generally, the dosimetric equipment has been calibrated in the certified radiation field or by using a radiation source which satisfies traceability on exposure, that has been ensured in the definition of exposure and/or absorbed dose. The conversion to the other radiation units from exposure or absorbed dose unit have been carried out by using calculated conversion factors or using measuring instruments of which the response characteristics are adjusted to be proportional to the objective dose. These facts imply that the present concept for calibration does not necessarily meet such recent requirements on dose evaluation. Under these situations we consider that the method evaluating dose from photon energy spectrum is more flexible than the present method and provides more reliable results to coincide with the present radiation protection concept, because energy information is available. To realize this technique it is need to prepare a reliable spectrum analysis program which combines the formation of accurate response functions of the detector and the stable spectrum unfolding method. This paper describes a method for interpolating accurately the response functions of $^{3}$°Spherical NaI(Tl) scintillation detector and the test results of dose evaluation by using a spectrum unfolding program with them.

2. EXAMPLES OF SPECTRUM UNFOLDING METHOD REPORTED UP TO NOW
In Japan, there are two representative methods for evaluating dose from pulse height spectrum measured. One is a group categorized in the unfolding analysis using response functions of the detector. (1,2,3,4) Other is G(E) function method which can directly obtain the dose value by applying spectrum-dose conversion operator to a pulse height spectrum. (5,6,7) The unfolding techniques mentioned above are effectively used in the fields of environmental radiation monitoring, but we consider that further improvement is need in the two points, that is, to prepare more accurate and large number of response functions more than 100 ranging from 40 keV up to 3.4 MeV. The interpolation method of response functions used here is basically the same as we tried in the past (4), but the present method is further improved in interpolation of relating parameters, simulation of the shape of individual component spectrum and the formation of complete response functions.

The response function is composed from each spectrum component resulting from various interaction of photons with NaI(Tl) scintillator, such as total absorption peak component, Compton absorption component, back scattering component, spectrum component accompanied with pair creation and annihilation, etc.. The present method is, at the first, decomposes the pulse height spectrum to each constituting component, mentioned above, and simultaneously the shape of each component spectrum is simulated by some modified exponential functions with parameters on spectrum shape. These parameters expressed as a function of photon energy is interpolated at an arbitrarily energy point. The complete response function is composed by superimposing each component spectrum which was calculated from exponential function using relating parameters. Details of this method is described in following chapters.

3. CALCULATION OF RESPONSE FUNCTIONS
1) Basic response functions calculated by a Monte Carlo method
We calculated the accurate response functions theoretically by using a Monte Carlo method. (8,9,10) In this calculation the physical processes of interaction in the detector are traced exactly. In one calculation case, a hundred thousand photons were assumed to be incident on the crystal. This corresponds to the photon flux of 2193 photons/cm². Resultantly, the accurate response functions were simulated. The accuracy of the response function is verified by the comparison with experimental measurements. (8)

These response functions were originally performed to determine the spectrum-dose conversion operator, namely the G(E) function, which calculates dose directly from a pulse height spectrum without tedious spectrum analysis. (11,12) At present, the G(E) functions for various types of NaI(Tl) scintillator are calculated and reported. (12) The response functions used for the interpolation of response function here is completely equal to that used for determination of G(E) function. (See Figure 1)
In interpolation calculation of response functions the effect of the scintillation efficiency of NaI(Tl) crystal is very important because it affects the spectral shape of pulse height distribution. Such effect is considered in original calculation of the response function.

2) Description on the detector

The configuration and shape and size of NaI(Tl) scintillator used in the calculation conforms to the Japanese Industrial Standard (JIS), and in original calculation the constitution of NaI(Tl) scintillation detector was modeled in the configuration consisting of NaI(Tl) crystal and a dummy aluminum disk placed in the backward, instead of photomultiplier tube and aluminum probe case.(7) In this paper are shown a method for decomposition and construction of response function and unfolding program on 3" φ spherical NaI(Tl) crystal.

3) Each component spectrum constituting response function

Important elements which constitute the response function are as follows. Total absorption energy and Compton edge energy are respectively expressed here to be E0 and Ec.

1. (1) Total absorption peak component from photoelectric absorption and multiple scattering,
2. (2) Compton absorption component distributing from 0 to Compton edge energy Ec,
3. (3) Compton scattering component from the canning and probe materials, distributing from E0-Ec to E0,
4. (4) Escape component due to a pair production interaction distributing from E0-1.02 MeV to E0.

The representative shape of each component spectrum are schematically shown in Figure 2.
4) Function and the relating parameters for determining the shape of energy distribution

There are many types of functions and the relating parameters to generate the pulse height spectrum of each component. The summary is described in the following.

1) Total absorption peak component

This consists of two components of the total absorption due to photoelectric absorption and multiple scattering. The absorbed energy of this two components is same. However, it is not equal as explained previously because the effect of scintillation efficiency is different in every energy absorption event in an interaction process. Here, the center of total absorption peak was supposed to be a weighted center of the total absorption pulses. The pulse height energy is normalized to 0.662 MeV at photon energy of 0.662 MeV. These apparent non-linear energies of response function were corrected to be proportional to the real photon energy. And also, the X-ray escape component in low energy range less than 0.4 MeV was treated separately from the total absorption peak and the contribution was superimposed on the final spectrum. The total efficiency, total absorption efficiency, scintillation efficiency and X-ray escape efficiency, are shown in Figure 3.

2) Spectrum component accompanying with Compton scattering

The spectrum due to Compton scattering mainly distributes in the energy region under Compton edge.

![Figure 3 Detection efficiencies of 3" φ spherical NaI(Tl) scintillation detector.](image)

Energy Ec, and in addition, the scattering components from detector canning and probe materials overlaps in the energy range from E0-Ec to E0. (Figure 4) The 180 degree Compton scattering component from surrounding materials appears at a point of E0-Ec. Otherwise, some fraction due to multiple scattering in the crystal distributes between Ec and E0. Here, these each spectral component was calculated using suitable functions separately and then, the response function was synthesized by overlapping these components. (Figure 5)

![Figure 4 Over-Compton component ranging from E0-Ec to E0.](image)

(Number of Input photons is 100,000)
(3) Escape component due to the electron pair production

The characteristic spectral distribution including single escape peak and double escape peak due to pair creation and annihilation process is very predominant in the high energy region. In this case the pulse height spectrum distributes in the energy region between E0-1.02 MeV and E0. In the region between single and double escape peaks and total absorption peak a Compton scattering component is distributed, and in addition, the tail composition appears in the energy region less than E0-1.02 MeV. (See Figure 2) These two spectral components were expressed by the different exponential functions. The total counts of component ranging from E0-1.02 to E0 MeV are shown in Fig. 6.

5) The formation of response functions.

There are many parameters and functions for interpolation, approximation to generate the shape of each component spectrum. By using various approximation and interpolation formula the parameters of the objective photon energy were interpolated and the pulse height distribution of each component were calculated by using the corresponding exponential functions. By accumulating each component spectrum the response function array was completed. This computer program can calculate response functions of 10keV width / bin and 10keV interval for photon energy in the range from 40 keV to 3.4 MeV. In Figure 7 the array of response function of 3 "φ spherical NaI(Tl) scintillation detector is shown. In this case the response function is broadened statistically. In unfolding calculation a little modified response function, of which the pulse resolution is adjusted properly according to the used spectrum unfolding techniques, is applied.
6) Preparation and test of the unfolding calculation program

(1) Calculation scheme of unfolding program and the performance

Unfolding calculation test was done about two cases. The one is a stripping method. This calculation flow carries out firstly the unfolding analysis of pulse height spectrum by using non broadened response function array and secondly the calculation process for sharpening for photon energy spectrum. The other case is a Gauss-Seidel iterative method. This case performs directly the unfolding calculation by using an array of broadened response functions. In this case the process for sharpening is not need. We tried this two methods and obtained the same results.

From theoretical point of view it is preferable to analyze the pulse height spectrum by using broadened response function adjusted to the resolution of measured practical data. However, since measured data intrinsically accompanies statistical error, the stable results could not necessarily obtain by a simple mathematical analysis because of a vibrational solution between adjacent bins. But by introducing some mathematical procedure to suppress the vibration and by applying a suitable resolution factor, consequently, we could settle these problems. The matrix of response function array of 340 x 340 was completed, which is corresponding to the range of 3.4 MeV.

(2) Reproducibility test on incident photon flux

We tried the unfolding calculation of original standard response functions for the performance test of the present response functions and unfolding analysis program. This test is important to check the accuracy of the interpolation of parameters and of the formation of response functions. The original response functions were of 28 photon energies from 40 keV to 10.0 MeV and the flux of incident photons to the detector was 2193 photons/cm². Figure 8 shows 24 photon energy spectra which were obtained by unfolding the original response functions up to 3.0 MeV by interpolated response functions, and the evaluated photon flux calculated by the Gauss-Seidel iterative method well agreed with the above theoretical incident photon flux. (See Figure 9) The error was less than 1 % in the range from 0.1 MeV to 3.0 MeV.
Figure 8  24 unfolded photon spectra analyzed by the spectrum analysis program.

Figure 9  The results of unfolding of original response functions by interpolated response functions.

(3) The comparison with G(E) function method
The original response functions utilized to calculate a G(E) function are same with those used for the interpolation of response functions here. Two results of the dose evaluation by the G(E) function method and the spectrum unfolding method agreed well in error of less than 1%, in wide energy range from 0.1 to 3.0 MeV. In energy range less than 0.1 MeV a little large discrepancy was observed.

(4) Analysis examples of practical pulse height spectra
A measured pulse height spectrum was obtained using a 60Co gamma radiation source under low scattering condition, but it was difficult to eliminate scattering contribution completely. In present case some scattering contribution is appeared in the low energy region. Unfolded results are shown in Figure 10 and 11.

Figure 10  Result of unfolding calculation test of 60Co pulse height spectrum data.
4. CONSIDERATIONS AND CONCLUSION

The results of interpolation of response functions and unfolding tests described above showed that the generated response functions have good reproducibility and the unfolding program is reliable. From unfolding test of original Monte Carlo pulse height spectra the evaluation error of photon flux were less than 1 % to the true input photon flux, and also, the results converted from flux to dose quantities such as air kerma and effective dose showed good agreements less than 1 % in error in comparison with G(E) function method. We carried out the same examination about 3φ x3φ NaI(Tl) scintillation detector and could obtain the same good results.

The reliability of current dosimetry system adopted in radiation protection fields is basically maintained by the traceability concept based on exposure unit. This system itself is very important and offers basic reliability of the radiation dosimetry system, but this does not flexibly meet the current situations of radiation protection dosimetry. When considering the variability of dosimetric technology, we think that the spectrometric technique developed here can improve the conversion error from the quantities of primary standard to the operational quantities and can present accurate and high reliable results in dose evaluation of various radiation protection quantities.

In the recent development of micro electronic devices and technology it is easy to compactly incorporate the analysis system into the measuring instruments, and versatile and accurate measuring system in compliance with the present radiation protection dosimetry can be realized.

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