90Sr Concentration in Cow Teeth from South Ural Region, Russia, Using Monte Carlo Simulation

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The Imaging Plate (IP) technique which uses the Monte Carlo code, MCNP, to convert IP response to 90Sr concentration with varied thickness of the standard source has been proposed in this study. In order to verify the validity of simulation calculation in the proposed method, the radial distribution of IP signal has been compared between calculation and experiment. The result is, they are in good agreement.

The proposed method has been applied to a cow tooth from the territory contaminated by radioactivity after the accident in the Mayak facility in the South Ural, Russia. Two samples have been prepared from the tooth, i.e., a thin sample of 1.2 ± 0.2 mm in thickness and a thick sample which is a half of the tooth. The IP response has been evaluated for the thick sample using experimentally made standard sources, and multiplied by a modification factor to decide that for the thin sample. The modification factor has been determined with MCNP to be 0.83 ± 0.08 for a thickness of 1.2 ± 0.2 mm. Using these values, 90Sr concentration has been estimated to be 0.11 Bq/g for the thin sample and 0.12 Bq/g for the thick sample, hence they are in good agreement.

INTRODUCTION

The presence of 90Sr in environmental and biological materials is mainly due to atmospheric nuclear weapon tests, nuclear waste discharges and nuclear accidents.1) This artificially produced radionuclide has high ecological importance because it is accumulated in bone tissues.2) For this reason 90Sr has been a principal subject for environmental monitoring and radioecological research. It is important to evaluate the amount of sampled 90Sr in evaluating its quantitative influence on the environment contaminated with the present radioactive nuclides.

Recently, a technique using the Imaging Plate (IP) has been applied for determining the 90Sr concentration in teeth.3) However, this IP technique has some difficulties in the determination of the absolute values. Though the standard sources which have various 90Sr concentrations and the same thickness as that of the measured sample are necessary, a difficulty is found in manufacturing them because the thickness of the obtained teeth is various. Moreover, the tooth sample is desired to be thin for improving the image resolution, but it is difficult to make thin standard sources precisely, e.g. 1 mm thickness, with uniform 90Sr distribution.

In order to avoid these difficulties, this study proposes the IP technique which uses a Monte Carlo code to convert IP response to 90Sr concentration with varied thickness of the standard sources instead of manufacturing them in reality. In other words, this method produces virtual thickness of the standard sources which leads to the advantage that it is applicable to samples with arbitrary thickness. Moreover, the results for thin tooth samples obtained with this method are important as fundamental data for the future plan to evaluate the 90Sr distribution at high resolution by deconvoluting the IP signal images.

The proposed method is tested on the determination of the 90Sr concentration in a cow tooth offered from the territory contaminated by radioactivity after the accident in the ‘Mayak’ facility in the South Ural, which was the first nuclear plant in the Soviet Union.
MATERIALS AND METHODS

Experiment
The Imaging Plate is a radiation sensor that records a distribution of the radioactive nuclei in the sample as an image. It is based on the principle that F centers are formed in BaF2Br:Er2+ by the beta rays from the radioactive nuclei contained in the sample.

To calibrate the response of the IP as a function of the 90Sr activity, three standard sources were used. The standard sources consist of a mixture of paraffin, powdered tooth dentin from Techa River area residents, and standard bone powder. They were melted into aluminum blocks, with 37.6, 20.9, 10.8 Bq/g of 90Sr.3)

The evaluation method for 90Sr activity proposed in this study was tested for a cow tooth from Mayak. The tooth was hardened in resin. Its central part was sliced using a low speed diamond saw along the length-wise direction into a slice 1.2 ± 0.2 mm in thickness and utilized as a thin sample. As a reference, one of the remaining bulk samples of the tooth was used as a thick sample. Then the flat side of the thick sample, the thin sample, and the standard sources were placed on the IP (Fuji BAS-IP MS 2025). The IP with the tooth samples and the standard sources was placed in a lead cave, which is for reducing the IP signal from background radiation, for the one week duration of the exposure. The data on the IP were read out by an image reader (Fuji imaging analyzer BAS-1500).

Calculation
The IP responses dependent on the 90Sr concentration included in the standard sources were modified using calculation. In the calculation, the energy spectrum of beta rays from 90Sr and its daughter nuclide, i.e. 90Y, was calculated by Fermi’s theory.4) The transport of those beta rays in the standard source and imaging plate was simulated with MCNP-4C code.5) The energy deposit was tallied in the probe regions of an imaging plate with various radii for varied thickness of the standard sources.

RESULT AND DISCUSSION

Validation of simulation calculation
The method was verified through an experiment using the above-mentioned standard sources of 3.5 mm thickness by comparing its result to the calculated data with respect to their radial distributions, i.e., for various value of tally radius. Figure 1 shows the result. The experimental data is the IP signal (originally in units ‘PSL/mm²’) and the calculated data is the energy deposit (originally ‘MeV/mm²’) within the tally of the radius specified on the horizontal axis, per unit tally area. The unit ‘PSL’ for experimental data is the abbreviation of Photo-Stimulated Luminescence, which is an arbitrary unit of IP signal peculiar to the measurement system and its condition.6) In the experiment, the tally corresponds to the region where the PSL value is computed and it was set using the software supplied with the BAS-1500. In order to compare the relative distributions, both data were normalized to 1 at the tally radius of 0.5 mm and so the unit of vertical axis is exhibited as an ‘arbitrary unit’. They are in good agreement, which suggests the validity of the calculation method used in the present study. In experimental data, PSL value in the region outside a radius of 6 mm was at the background level. Therefore, a region of 6 mm radius was used in determining the IP response using the standard sources experimentally and modifying it by calculation.

Modification factor of IP response
The IP response was modified using the above-mentioned calculations for the standard sources with various thickness for a tally radius of 6 mm. The IP response ratio for each thickness up to a thickness of 3.5 mm is defined as the modification factor and shown in Fig. 2. Exhibited modification factors should be multiplied with the experimental response to the 3.5 mm thick standard source to get the IP response for the necessary thickness. The plotted data are fitted by an expression of form

![Fig. 1. Comparison between distributions of measured IP signal and calculated energy deposit. The plots are normalized at a tally radius of 5 mm.](http://jrr.jstage.jst.go.jp)
Evaluation of $^{90}$Sr Concentration Using IP

MF = 1.0065 * $(1-e^{-1.418 \times t})$, (1)

where MF is the modification factor for the sample thickness of $t$ (mm).

The modification factor for thickness of 3.5 mm and over is almost constant. This suggests that beta rays emitted at a depth over 3.5 mm scarcely reach the probe region of the imaging plate. Therefore, assuming the uniform distribution of $^{90}$Sr, the standard source of 3.5 mm thickness is applicable to tooth samples with thickness of 3.5 mm and over without using a modification factor. For thickness below 3.5 mm, the modification factor changes rapidly. These geometries are expected to improve the resolution of IP images. On the contrary, the fluctuation of the IP response by the variation of the thickness increases in these cases, which means that precise control and evaluation of the thickness will be more necessary.

Application to Mayak teeth

The proposed method was tested for evaluation of $^{90}$Sr concentration in the cow tooth. The IP response for 3.5 mm thick standard sources is in Fig. 3. Using linear regression, the IP response was found to be

$$y = 16.5 \times x$$

where $y$ is the IP signal divided by the area of the sample (PSL/mm$^2$) and $x$ is the $^{90}$Sr activity (Bq/g). Here, the error of the IP response is estimated to be 4% from regression analysis. In computing the PSL value for the tooth samples, the tallies were chosen so that its edge is at least 2 mm away from the sample, because the PSL values at these locations were at the background level for the resin region surrounding the sample. Equation (2) is applied for the PSL value for the thick sample, to give a $^{90}$Sr concentration of $0.12 \pm 0.04$ Bq/g. The uncertainty corresponds to 39% and it is derived from the fluctuation of the PSL value by possible deviation in choosing the tally of 5%, the error of the sample area due to deviation in measurement and complex shape of 38%, and the error of IP response of 4%. As to sample area, the region of the surface which is covered with the resin is treated as the error.

The modification factor of IP response for the thin sample, i.e. 1.245 mm, was estimated to be 0.83 using equation (1). Thus, the equation for the thin sample is

$$y = 16.5 \times 0.83 \times x = 13.7 \times x.$$  (3)

Here, the resultant IP response of 13.7 has an uncertainty of around 10%, which is derived from regression analysis of the equation (1) of 0.2% and (2) of 4%, and the deviation of the modification factor due to standard deviation of the measured thickness of 9%. Using equation (3), the thin sample was estimated to contain $0.11 \pm 0.02$ Bq/g. Here, the uncertainty is 14% and it consists of the fluctuation of the PSL value by possible deviation in choosing the tally of 10%, the error of the sample area (0.6%), and the error of IP response (10%). These results are summarized in Table 1. The sample surfaces in contact with the IP are originally located at most a few mm away in the tooth from each other, considering that a thin layer of the tooth disappears in the cutting process. The agreement of the estimated $^{90}$Sr concentrations between two samples supports the validity of the proposed method.

The area of the samples needed in estimating the $^{90}$Sr concentration is measured at the surface in contact with the IP. The uncertainty of the measured sample area is considered to be more severe as the sample thickness increases because the area of the sample near its edge decreases rapidly. On the other hand, uncertainty in measuring the thickness is more

![Fig. 2. Modification factor normalized to 1 at a thickness of 3.5 mm (IP response ratio of each thickness relative to 3.5 mm thick standard source)](image)

![Fig. 3. IP response for standard sources. By fitting these, IP response was decided for a standard source of 3.5 mm in thickness. This response was also utilized in evaluating $^{90}$Sr concentration in the thick tooth sample.](image)
influential for thin samples according to Fig 2. In preparing thin samples, precise control of uniformity in thickness is essential. If control is difficult, the practical way is to divide the tooth into small pieces with relatively uniform thickness.

CONCLUSION

An IP technique which uses Monte Carlo code to convert IP response against $^{90}$Sr concentration with varied thickness of the standard source was proposed in this study. The validity of simulation calculation in the proposed method was verified through an experiment using a standard source including known concentrations of $^{90}$Sr.

The proposed method was tested on the determination of the $^{90}$Sr concentration in a tooth of a cow from Mayak. The modification factor of IP response for 1.2 ± 0.2 mm thickness is 0.83 ± 0.08, where that for 3.5 mm is set at 1. Using this value, the $^{90}$Sr concentration for a 1.2 ± 0.2 mm thick sample was estimated to be 0.11 Bq/g, and the bulk of the tooth to be 0.12 Bq/g. This agreement of the estimated $^{90}$Sr concentrations between two samples supports the validity of the proposed method. However, the fluctuations of the sample thickness for thin samples are very influential on the modification factor. In preparing thin sample, precise control of uniformity in thickness is essential. If control is difficult, the practical way is to divide the tooth into small pieces with relatively uniform thickness.