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# Numerical Study on Range Measurement System with Positron Camera

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## INTRODUCTION

An irradiation system is now being developing at the secondary beam course [1] of HIMAC. The system has a remarkable feature for heavy-ion radiotherapy, namely, the positron emitter beam,$^{11}$C, gives information of its range in a body by detecting pairs of annihilation gamma rays from the body.

The apparatus of the range measurement system is illustrated in Fig. 1. Before irradiation for radiotherapy, an examination beam of $^{11}$C, which is collimated with a pencil-beam collimator, is scanned laterally with a pair of scanning magnets and distally with a range shifter up to a position of interest, e.g., quit close to a critical organ. A positron camera, consisting of a pair of Anger-type scintillation detectors [2], detects the pairs of gamma rays and determines the stopping position of the beam. Each detector is equipped with a NaI(Tl) crystal having a diameter of 600 mm and a thickness of 30 mm [3]. In view of the good spatial resolution, the surface of the crystal was considered to be diffusively reflective at the front and absorbent at the edge [4].

The purpose of this paper is to demonstrate numerically that the range in a body can be measured with accuracy of less than 1 mm under the limitation that the irradiation for examination has to be less than a few percent of the therapeutic one.

## SIMULATIONS

### 1. *Spatial resolution of positron camera*

### 1.1. *Gamma ray deposition distribution*

Since some annihilation gamma rays lose their energy in multiple reactions in the crystal, their energy deposition points cause a lateral dispersion ($\sigma_{dep}$). The deposition points and

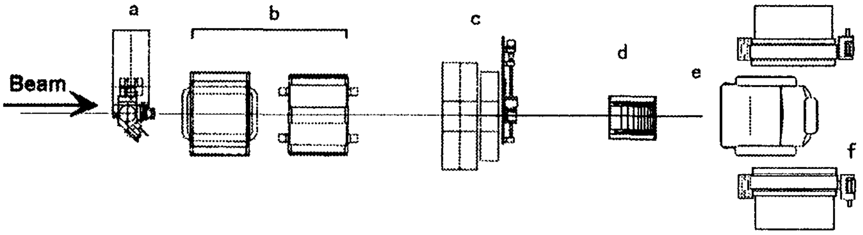

Fig. 1. Schematic diagram of range measurement system. **a** : pencil beam collimator, **b** : a pair of scanning magnets, **c** : beam monitors, **d** : range shifter, **e** : chair for therapy, **f** : positron camera.

deposited energies were calculated with a Monte Carlo program, GEANT [5], and the lateral and the distal distributions were obtained with centroid calculation. The thickness of the crystal was modified in the calculation in correspondence with the average incident angle of the gamma rays.

### 1.2. *Calculation error on a detector*

The calculation error of a scintillation detector was estimated for incident points$(y, z)$ of gamma rays into the crystal.

The light distribution on the surface where the photomultipliers are mounted was calculated numerically to estimate the numbers of photoelectrons emitted from the photocathodes of the photomultipliers. The distribution, dependent on height $(x)$ of a scintillation point$(x,y,z)$ (an energy deposition point of a gamma ray) from the boundary between the photomultipliers and the light guide of a glass plate, is given by

$$f(u,v;\ x,y,z) = f_{\mathrm{dir}}(u,v;\ x,y,z) + f_{\mathrm{ref}}(u,v;\ x,y,z) \quad ,$$

where $(u,v)$ is the point on the surface where the photomultipliers are mounted, and $f_{\mathrm{dir}}$ and $f_{\mathrm{ref}}$ are the distributions for the direct light from the scintillation point and for the light reflected by the incident surface, respectively.

A number of scintillation lights which arrive on a photomultiplier is derived by integrating the light distribution on the photocathode area. The scintillation point$(y,z)$ is determined by centroid calculation of the numbers of photoelectrons.

The calculation error for the detector, $\sigma_{\mathrm{cal}}$, was calculated with the distribution of depths of the scintillation (energy deposition) points; the error consists of the statistical error of photoelectrons and the deviation of calculated points caused by the difference in depth.

### 1.3. *Parallax effect*

Because the thick crystals are used in the positron camera, parallax, dependent on the incident angles of the gamma rays, affects the calculation of the point at which the positron emitter beam stops.

The stopping point of the beam is determined by $(Z_1+Z_2)/2$, where $Z_1$ and $Z_2$ are the points measured with the detector-1 and detector-2, respectively. When the distribution of the deposition points of the gamma rays is homogeneous, the parallax effect is $t_{\mathrm{cry}} \times \tan(\theta)/2$ in FWHM, where $t_{\mathrm{cry}}$ and $\theta$ are the thickness of the crystal and the incident angle into the crystal, respectively. The deviation of the parallax, $\sigma_{\mathrm{par}}$, was modified by using the distal distribution calculated in section 1.1.

### 1.4. *Spatial resolution of positron camera*

The resolution is given by

$$\sigma_{\mathrm{cam}}^2 = \sigma_{\mathrm{dep}}^2/2 + \sigma_{\mathrm{cal}}^2/2 + \sigma_{\mathrm{par}}^2 \quad ,$$

where the first and the second term in the right-hand part of the equation are resolutions of a scintillation detector, and the factors 1/2 of the terms correspond to the average positions of two detectors.

The estimated resolution is estimated at 5.0 mm as listed in Table 1.

| Deposition; $\sigma_{dep}$ (mm) | Calculation; $\sigma_{cal}$ (mm) | Parallax; $\sigma_{par}$ (mm) | Total resolution; $\sigma_{cam}$ (mm) |
|---|---|---|---|
| 5.7 | 1.5 | 2.8 | 5.0 |

Table 1. Spatial resolution of positron camera

The deviations, $\sigma_{dep}$ and $\sigma_{cal}$, are those of a constitutive detector.

## 2. *Number of positron emitters and their distribution*

In view of the need to prevent damage to normal tissues, irradiation for examination is subject to a quantitative limitation.

The momentum distribution of the incident beam was measured [6] to calculate the dose in a body. It is necessary that the range spread be comparable to the margin of the irradiation field at the most, and thus, the momentum width has to be limited.

A density distribution of the positron emitters was calculated by HIBRAC, a code based on the work by Sihver et al [7]. When the energy of $^{11}$C was 300 MeV/u, the range straggling was 0.4 mm, and the range spread, $\Delta_r$, was 3.7 mm for 0.8 percent of momentum spread. The density distribution obtained is indicated by the dotted line in Fig. 2.

The depth-dose distribution under the condition was also calculated with the code. The physical and the biological doses are, respectively, illustrated with the solid and the dashed lines in Fig. 2. Here we assumed that the number of incident particles, the beam radius and the density of the body are $n_b$=7.9×10$^4$, $\sigma_b$=0.3 mm and 1 g/cm$^3$, respectively, and consequently, the biological dose was about one percent of dairy therapeutic one. The $^{11}$C's survival rate at the stopping point was 0.5, and therefore, the particle, $n_s$, of 4.0×10$^4$ would be used as the positron emitter sources.

## 3. *Number of gamma pairs detected and range accuracy*

A number of detecting gamma pairs, $n_e$, is written as

$$n_e = 2\,\Omega\,\varepsilon_c T_c n_s(1\text{-exp}(-t/\tau)) \ ,$$

where $\Omega$, $\varepsilon_c$, $T_c$, $t$ and $\tau$ are the solid angle for a constitutive detector, the detection efficiency for a pair gamma ray, the survival rate at the fronts of the detectors for a pair of gamma rays, the measurement time and the time constant of $^{11}$C's decay, respectively.

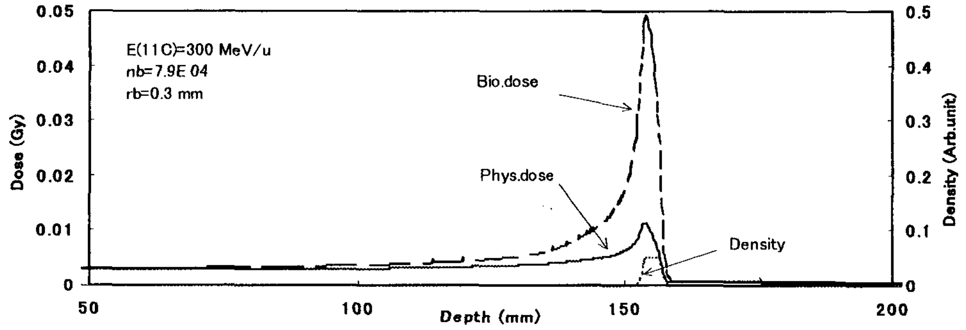

Fig. 2. Depth distributions of 11C's density. Physical dose and biological dose were calculated with HIBRAC.

The parameters were $\Omega$=0.14 sr, $\varepsilon_c$=0.49, $\tau$=29.3 min, and assumed to be $T_c$=0.15 and $t$=10 min, where the detection efficiency was corrected with the average incident angle of gamma rays. The number of events was estimated at $n_e$=238.

*When the distribution of measured* $^{11}C$ *points is approximately Gaussian, the accuracy of* the range is obtained by $\sigma / n_e^{1/2}$, where $\sigma$ is the deviation of the Gaussian distribution. Here $\sigma$ was estimated as

$$\sigma^2 = \sigma_{cam}^2 + (\Delta_r/2)^2 ,$$

and consequently, $\sigma$=5.3 mm and the accuracy of the range was estimated to be 0.3 mm.

## DISCUSSIONS

The number of events detected was estimated without the energy gate. To prevent contamination by scattered gamma rays in the body, it may be necessary to select events with the energy deposited in each crystal. Though the number of events detected decreases to about a quarter in this case, the accuracy in the range of less than 1 mm is achieved.

The collimated beam will be used as an examining one, and so the number of positron emitter sources will probably be limited because the beam should be irradiated in a short time so as to preclude the effect of particle decay. Regarding future work, the study of the characteristics of the irradiation beam is one of the subjects to be tackled next.

## CONCLUSION

It has been found by numerical simulations that the range accuracy of less than 1mm will be achieved in the case of using the secondary beams at HIMAC. The certification of the range before therapeutic irradiation is useful for reducing a margin of irradiation field when the tissue is near a critical organ. The positron camera system is now being produced and its characteristics, notably the spatial resolution and the detection efficiency, will soon be measured.

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