ROTATIONAL POSITRON COMPUTED TOMOGRAPHS

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Abstract

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A description and analysis are presented of positron-emission computed tomographs which utilize the continuous rotation scan of a ring detector array. The detectors are arranged in a particular irregularity determined by a computer. The aim of the rotation scan is to exceed the sampling requirement to recover intrinsic detector resolution with high sampling redundancy. It has already been shown that fine and uniform sampling can be achieved with continuous multiple rotation. To obtain an angularly invariant sampling with limited angle (<360°) rotation, the angle of rotation must be 360°/n where n is an odd integer (≥3), and the detector array should be composed of n identical subarrays arranged in every 360°/n. The detectors must also be arranged on a non-circular ring to avoid concentration of sampling points. An example of a detector array for 120° rotation (n=3) shows excellent sampling characteristics. The effect of linear and angular sampling on spatial resolution is discussed taking into account the smoothing effect of data binning. It is shown that the smoothing effect is not appreciable if the Nyquist frequencies for sampling are properly chosen. A rotary positron tomograph, Positologica, which has been developed for brain study, has a circular array of 64 BGO crystals. The spatial resolution is 5.8 mm FWHM at the centre and less than 9 mm FWHM in the field of view. The point spread functions well reflect the results of theoretical analysis.

1. INTRODUCTION

One aim in recent improvements in positron-emission computed tomography (PECT) is high detection sensitivity with high spatial resolution. A circular ring array of BGO crystals is a suitable choice for this goal at present. In the ring system, the geometric sampling problem is of particular importance, because the linear sampling interval in the stationary mode is not fine enough to recover the resolution capability of detectors. The half detector angle rotation can halve the sampling interval [1], but is still insufficient for optimization. A wobbling motion is therefore implemented in some recent devices [2, 3].

We have proposed the continuous rotation of a ring array of detectors arranged with a particular non-uniform spacing [4]. The advantage of the rotational scan is that fine and uniform sampling is achieved with high sampling redundancy. The high sampling redundancy reduces the effect of the instability of the detector gain.

The continuous rotation scan is divided into two types: multiple rotation and limited angle (<360°) rotation. The former can offer a rather arbitrary scan speed, but some design complexity is inevitable because of the electric power supply to the rotary part and data transmission from the rotary part to the stationary part. We have recently developed a system of this type for brain study using 64 BGO crystals [5, 6]. In this system, electric power is supplied through a slip ring, and data transmission is made through a parallel multi-bit rotary photocoupler. In the limited angle rotation type, a 360° rotation may be feasible, but a smaller angle rotation may be preferable mechanically if the required sampling property is achieved.

The sampling problems in the rotational PECT are discussed together with a description of the performance of our head PECT system with emphasis on spatial resolution.

2. DETECTOR ARRANGEMENT

A feature of the rotational PECT is that the detectors are arranged on a ring so that the sampling density in projections is as uniform as possible in the range of interest, where the sampling density is the number of coincidence lines falling in a projection bin. The arrangement can be determined by trial and error or by a computer iteration search program, the latter method giving better results [7, 8]. In the iteration method, the position of each detector is moved along the ring separately in turn, and at each step the detector is fixed at a position where a certain figure of merit on the sampling density uniformity is maximized. The cycle of iteration is repeated until all detectors no longer move.

An irregular arrangement requires a certain amount of marginal space between detectors, and may result in reduction of geometric efficiency. In the 360° rotation, however, it has been shown that a small total margin (in 360°) of the order of one detector width is sufficient to obtain satisfactory sampling characteristics. Distributions of both the sampling densities and detector sensitivities in projections are independent of the view angle. This property simplifies the correction of projection data for non-uniformity of the distributions.

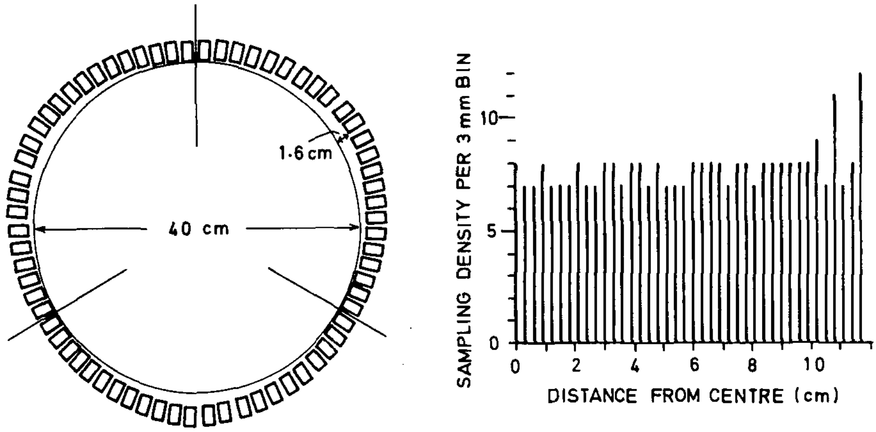

FIG.1. Detector arrangement for a 120° rotation system and its sampling density distribution.

In the smaller angle (<360°) rotation, the sampling density distribution generally depends on the view angle, which in practice is not convenient. A possible way of realizing angularly invariant sampling is to divide the entire circle into n(=integer) identical segments, and to allocate identical sub-arrays into them. The angular range of rotation is 360°/n. In such arrays, however, sampling points concentrate at distances $\pm R_d \cos(m\pi/n)$ from the centre, where R_d is the detector ring radius and m is a positive integer smaller than n. If n is even, a concentration occurs at the centre of the projections, and hence n must be odd.

For n=3 (120° rotation), concentrations occur at $R = \pm R_d/2$. One way to avoid the concentrations is to arrange the detectors on a non-circular ring so that the detectors in each segment have different distances from the centre. Figure 1 shows an example of such arrays and its sampling density distribution. The arrangement is searched by computer iteration assuming that the minimum centre-to-centre spacing of detectors is 16 mm whereas the average spacing is 18.2 mm. The distance of the detectors from the centre is changed linearly with the angle in a range 20–21.6 cm.

3. EFFECT OF SAMPLING ON THE SPATIAL RESOLUTION

If we neglect the positron range and angular deviation of the annihilation photons, the in-plane spatial resolution is limited by the spatial resolution of the detectors and the resolution imposed by linear and angular sampling. We shall

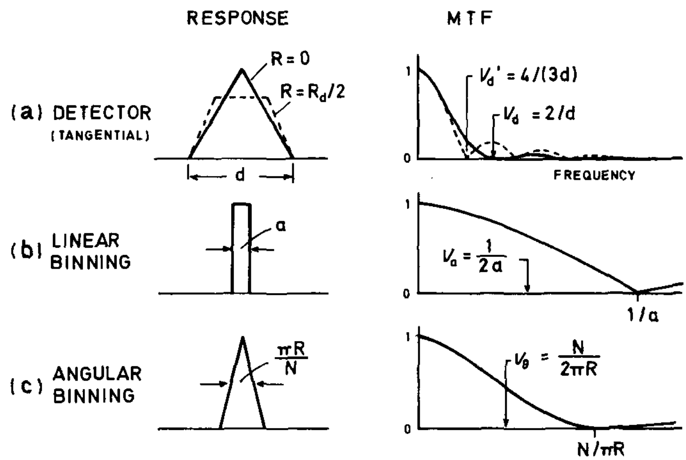

FIG.2. Detector resolution and smoothing effect of binning in linear and angular sampling.

consider first the detector response for the coincidence detection assuming rectangular detectors (crystals). The spillar effect of photons from detectors is neglected.

The detector response at the ring centre is isotropic, and is triangular with a FWHM equal to half the detector width d. The response at an off-centre position is not isotropic, and its shape is represented by a radial and tangential response. (Note that these responses refer to the detector and not to the reconstructed images.) The radial response is usually broadened with increasing distance from the centre, but the broadening is improved by the use of shielding septa between the crystals. The tangential response becomes more rectangular as the distance and the FWHM increases accordingly. In Fig.2(a), the tangential response and its MTF (modulation transfer function) are shown for R = 0 and $R = R_d/2$. The two MTFs go to zero at $\nu_d = 2/d$ and $\nu'_d \doteq 4/(3d)$ respectively, although these MTFs still have higher frequency components.

In the rotational PECT, the original sampling points in projections distribute randomly, and binning of projections with a sampling interval, a, is equivalent to applying rectangular smoothing to the original projections before the sampling. The smoothing function and its MTF are shown in Fig.2(b). The MTF goes to zero at 1/a, which is twice as high as the Nyquist frequency, $\nu_a = 1/(2a)$, of the linear sampling.

Angular binning of projections imposes tangential smoothing on the detector response at the off-centre positions. The angle of a coincidence line is obtained by summing the angle of a rotating gantry and the angle of the line with respect to co-ordinates fixed at the gantry. If both the angles are binned with $\Delta\theta$

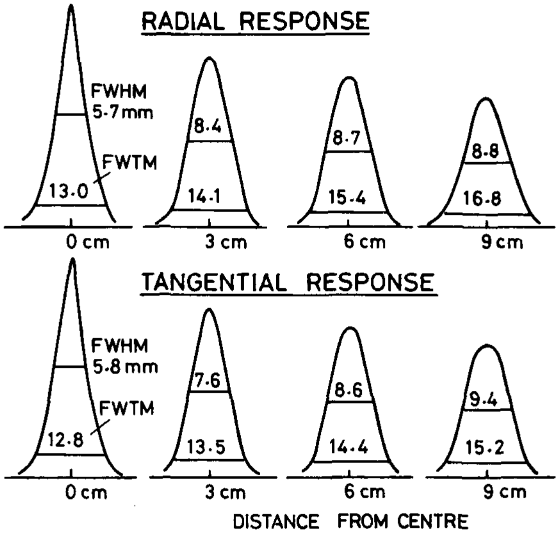

FIG.3. Responses of the rotary positron tomograph Positologica for a line source (^{68}Ga, 2 mm Φ) at various points.

independently, the response function of the tangential smoothing at distance R is triangular with a FWHM equal to $R\Delta\theta = \pi R/N$, where N is the number of views (see Fig.2(c)). The MTF of the angular smoothing goes to zero at $N/(\pi R)$ which is twice as high as the Nyquist frequency, $\nu_\theta = N/(2\pi R)$, of the angular sampling. (The response is somewhat improved by finer sampling of two angles before summation.)

From the remarks above on the MTFs and from the requirements imposed by the sampling theorem for accurate (i.e. artifact-free) image reconstruction, a reasonable choice of the sampling interval will be $\nu_a \geqslant \nu_d$ and $\nu_\theta \geqslant \nu_d'$ if we neglect the higher frequency components of the detector response, or more preferably $\nu_a \cong (3/2)\nu_d$ and $\nu_\theta \cong \nu_d$ taking into consideration the higher frequency. The latter choice is rewritten as

$$a \cong d/6 \qquad \text{and} \qquad N \cong 4\pi R/d \qquad (1)$$

With this choice, image blurring due to the smoothing effects of both the linear and angular binning are not appreciable.

4. A PROTOTYPE ROTARY POSITRON TOMOGRAPH: POSITOLOGICA

A positron tomograph of the continuous multiple rotation type has been developed for studying the human brain. The device has a circular array of 64

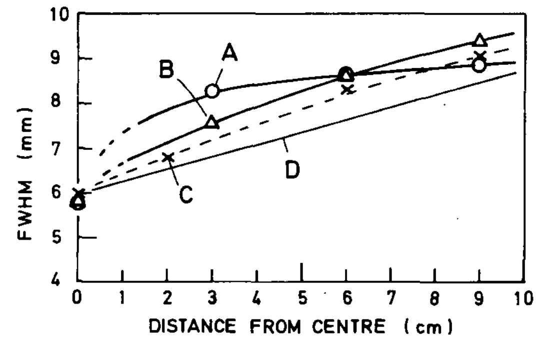

FIG.4. FWHMs of the responses of the Positologica. Experimental data are for a line source of 2 mm Φ.
A: Radial response of reconstructed image.
B: Tangential response of reconstructed image.
C: Tangential response observed in projection.
D: Tangential geometric response of detectors.

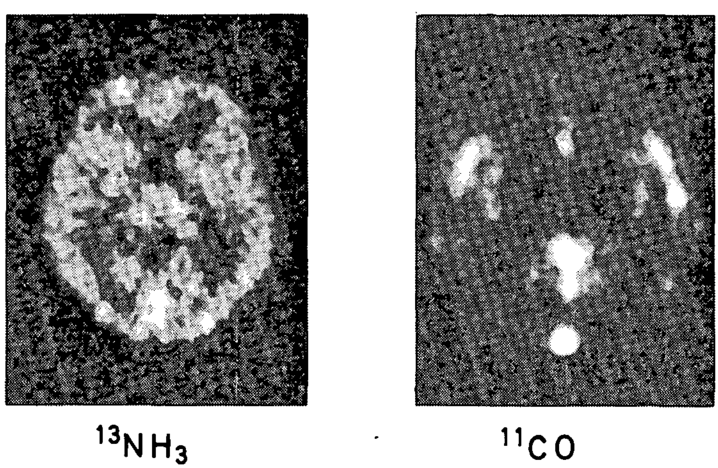

FIG.5. Images of $^{13}NH_3$ and ^{11}CO obtained with a normal subject (OM + 4 cm). Total counts are about 2×10^6 each. Photon absorption was corrected by transmission data.

12 × 20 × 26mm BGO crystals which is rotated at a speed of 60 rev/min. The detector ring radius is 22 cm. Taking into consideration the sampling requirement given by Eq.(1), we adopted the sampling interval a = 2 mm (=d/6) and the number of views N = 128 ($\cong 4\pi R/d$ for R = 12 cm). The detector arrangement was determined by computer iteration. The sampling density per 2 mm bin is 11.9 average, with a minimum of 11, in the field of view. The sensitivity is about 17 k counts$\cdot s^{-1}$ per μCi$\cdot$ml for a 20 cm Ø water phantom with 2 cm slice.[1]

Figure 3 shows the response functions of reconstructed images of a line source (^{68}Ga, 2mm Ø) placed in air perpendicularly to the detector plane. Figure 4 shows various FWHMs as functions of the distance from the centre. The excellent resolution at the centre is because the position corresponds exactly to a sampling point for all views, and this fact decreases blurring from linear binning, source size, angular deviation of photons, etc. The radial response at off-centre will be improved by the use of a septal shield between the crystals. Figure 5 shows images of $^{13}NH_3$ and ^{11}CO obtained with a normal subject.

5. CONCLUSION

It has been shown that the rotational PECT provides a sampling capability to recover the principal component of the detector resolution by a suitable choice of linear and angular sampling intervals. In the limited angle (120°) rotation, a satisfactory sampling characteristic can be obtained with a non-circular array of detectors.

The rotary PECT system, Positologica, gives an excellent imaging performance, although the practical resolution capability may be limited by the necessity of software smoothing to improve counting statistics.

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[1] 1 Ci = 3.70×10^{10} Bq.

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