COMPONENT RESOLUTION INDICES FOR SCINTILLATION CAMERA SYSTEMS

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From published overall resolution indices for three Anger camera systems, measured with three straight-bore collimators and ^{99m}Tc in air and with a water absorber present, the components due to inherent camera resolution, collimator geometry, and scatter are derived at various depths. Replacement of S-11 multiplier phototubes by bialkali phototubes improves calculated inherent Pho/Gamma III camera resolution by about 30% and by a further 33% upgrading to a high-performance model. At distances 2, 5, 8, and 10 cm from each collimator face with an intervening water absorber, mean scatter components of overall resolution indices are 6, 8, 9, and 10 mm, respectively. In typical clinical ^{99m}Tc imaging situations with a scattering medium present, the relative contributions of camera, collimator, and scatter to the total overall system resolution are presented.

Overall collimator-camera resolution indices for ^{99m}Tc were recently measured (*1*) in air and water for three Pho/Gamma cameras (one III model, initially with conventional S-11 phototubes and later with bialkali phototubes, and one updated high-performance (HP) model) with three straight-bore collimators (iodine, technetium, and high-sensitivity, with approximately 1,000, 4,000, and 15,000 holes, respectively). This paper presents some quantitative estimates derived from the measured overall resolution indices (*1*) of the components due to inherent camera resolution, collimator, and scatter.

METHOD

Neglecting scatter and septal penetration, the geometric resolution index R_g at distance b from the surface of a straight-bore collimator can be calculated from the equation (*2*):

$$R_g = \frac{d(a_e + b + c)}{a_e} \qquad (1)$$

where d is hole width, b is source-to-collimator distance, c is distance between collimator and central plane of crystal (1.27 cm), a_e is $a - 2\,\mu^{-1}$, a is collimator length, and μ^{-1} is mean free path (0.038 cm in lead for 140-keV gamma ray of ^{99m}Tc (*2*)). The physical dimensions of the collimators were accurately measured. The lengths of the 1,000-, 4,000-, and 15,000-hole collimators are 7.7, 4.45, and 1.6 cm, respectively, and their hole cross sections are circular (diam 0.6 cm), square (side 0.247 cm), and triangular (side 0.234 cm), respectively. R_g values were obtained for those distances at which overall resolution indices were measured with each camera.

Neglecting scatter and septal penetration and assuming a noise-free situation, the inherent resolution index R_i of the camera alone is related to the overall resolution index measured in air R_0(air) and the geometric resolution index R_g of a parallel-hole collimator by the equation (*3,4*):

$$R_0^2(\text{air}) = R_g^2 + R_i^2 \qquad (2)$$

Hence, R_i values were calculated for each camera using the appropriate R_0(air) and R_g values in each situation and are summarized in Table 1.

With water present as an absorbing and scattering medium, measured overall resolution indices R_0(water) are larger than corresponding values determined in air R_0(air) because of a scatter component, R_s, which may be evaluated from the equation:

$$R_0^2(\text{water}) = R_0^2(\text{air}) + R_s^2 = R_g^2 + R_i^2 + R_s^2 \qquad (3)$$

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TABLE 1. MEAN INHERENT CAMERA RESOLUTION INDICES R_i (MM) CALCULATED FROM GEOMETRIC COLLIMATOR RESOLUTION INDICES R_g AND MEASURED OVERALL RESOLUTION INDICES R_0 (AIR)

		Straight-bore collimator			Distance from collimator face (cm)			
Pho/Gamma camera	Range	15,000-hole	4,000-hole	1,000-hole	1	5	11	Overall mean
III with S-11 tubes	15–19	16	16	18	17	17	17	17
III with bialkali tubes	9–16	11	13	12	12	12	13	12
HP	5–11	7	10	7	9	7	8	8

Hence, R_s values were calculated for each depth for which measured R_0(water) values were published (*1*), using the appropriate calculated R_g and R_i values in each situation, and are summarized in Table 2.

RESULTS AND DISCUSSION

Figure 1 illustrates transmission scintigraphs obtained with the three cameras using ^{57}Co, a lead strip lattice, and no collimator and shows qualitatively that the inherent resolution determined by the smallest resolvable separation between adjacent lead strips successively improves. The results presented in Table 1 show that calculated inherent Pho/Gamma III resolution in air improves from a mean of 17 mm to 12 mm (29% decrease) with bialkali phototubes compared with S-11 tubes. Upgrading to the HP model improves inherent resolution by a further 33% to a calculated mean index of 8 mm. Multiplier phototubes with bialkali photocathodes have 1.5–2 times the quantum efficiency of conventional phototubes with S-11 photocathodes and therefore should improve the inherent camera resolution index according to the inverse ratio of the square roots of the quantum efficiencies for the same gamma-ray energy (*2*), namely by a factor 0.71–0.82. The mean calculated inherent resolution index in air of the gamma camera with bialkali phototubes is 0.71 times that with S-11 phototubes (Table 1). This is in good agreement with theoretical expectation and with the reported measured ratio of inherent camera resolution indices, 0.75 (*5,6*).

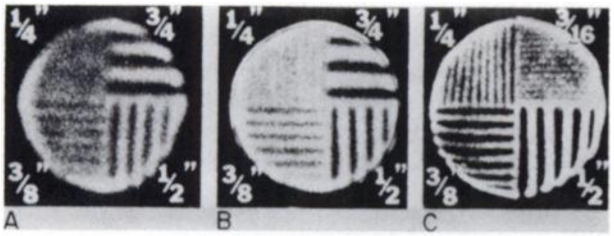

FIG. 1. Transmission scintigraphs recorded with ^{57}Co and lead strip lattice showing inherent resolution of three camera systems: (A) Pho/Gamma III camera with S-11 phototubes; (B) Pho/Gamma III camera with bialkali phototubes; and (C) Pho/Gamma HP camera.

The results presented in Table 1 show that, as expected, the calculated inherent resolution indices for each camera are independent of collimator and distance from each collimator face. The ranges given in Table 1 reflect the variations in the overall resolution indices measured over the detecting area (*1*) and the neglect of scatter in Eqs. (1) and (2).

The 1,000-, 4,000-, and 15,000-hole collimators have septal thicknesses (t) of about 3, 1, and 0.1 mm, respectively. The shortest distance a gamma ray can travel through septal material when taking the unwanted path of minimum attenuation is $w = at/(2d + t)$ (*2*). Utilizing the measured parameters of the 1,000-, 4,000-, and 15,000-hole collimators, w values of 1.54, 0.75, and 0.033 cm, respectively, are obtained, which are 41, 20, and 0.9 times the mean free path in lead (0.038 cm) of the 140-keV gamma ray of ^{99m}Tc and correspond to 100, 100, and 60% attenuation, respectively. Hence, septal penetration clearly occurs when the 15,000-hole high-sensitivity collimator is employed for ^{99m}Tc imaging. However, its neglect in the above equations has no observable effect on the derived inherent camera resolution indices which, as seen in Table 1, are no greater with the 15,000-hole collimator employed for the overall collimator-camera resolution index measurements than with the other two straight-bore collimators with which septal penetration does not occur. This is explained by the fact that, although septal penetration does contribute to the broadening of the measured line-spread function of the camera-collimator system, the broadening is generally below the level at which the resolution index, the full-width at half-maximum, is determined, and hence septal penetration effects would not be observable from resolution index measurements alone. Modulation-transfer function curves for the camera-collimator system (*1*) utilize the entire line-spread function and therefore account for septal penetration effects.

At 2, 5, 8, 10 cm from each collimator face with

TABLE 2. COMPONENTS OF OVERALL RESOLUTION INDICES R_0 FOR ^{99m}Tc IMAGING IN SCATTERING MEDIUM WITH PHO/GAMMA HP CAMERA AND 20% PHOTOPEAK WINDOW

Distance from collimator face (cm)	Straight-bore collimator (No. of holes)	R_i (mm)	R_s (mm)	R_g (mm)	R_0 (mm) $= \sqrt{R_i^2 + R_s^2 + R_g^2}$
2	15,000	8	6	6	13
2	4,000	8	6	5	12
2	1,000	8	6	9	14
5	15,000	8	8	10	16
5	4,000	8	8	7	13
5	1,000	8	8	11	16
8	15,000	8	9	13	19
8	4,000	8	9	9	15
8	1,000	8	9	13	18
10	15,000	8	10	16	22
10	4,000	8	10	10	17
10	1,000	8	10	15	20

an intervening water absorber, mean scatter components R_s of the resolution indices are found to be 6, 8, 9, 10 mm, respectively, (Table 2), using a 20% photopeak window with each gamma camera. The increasing effect of scatter with increasing depth is apparent. Pulse-height selection is not able to remove all the radiation that undergoes Compton scattering in surrounding tissue. Assuming a radioactive source 3 in. below the surface of soft tissue, Anger (*2*) has performed single-hit calculations for different gamma-ray energies and obtained rough indications of the fractions of Compton-scattered gamma rays which are removed by pulse-height selection. About 31% of the 140-keV gamma rays of ^{99m}Tc escape the subject without scatter or absorption and about 67% undergo Compton scattering. Even with pulse-height selection about 18% of the original gamma rays are Compton-scattered through sufficiently small angles that the resultant energy reductions are small enough for them to pass through the energy window and be detected, with consequent reduction in image quality and resolution capability, as evidenced by the results presented in this paper.

Table 2 summarizes the components of overall resolution indices for the Pho/Gamma HP camera since it has the best inherent resolution of the three cameras studied for the 20% photopeak window employed experimentally (*1*) and at distances 2, 5, 8, and 10 cm from each collimator face. The components R_i, R_s, and R_g of the overall resolution index R_0 due to the camera, scatter, and the collimator, respectively, are the same order of magnitude. For all but the smallest distances from the collimator face, the largest contributor to the overall resolution index is generally the collimator, with scatter the next largest, and inherent HP camera resolution least. At small depths, however, resolution loss due to scatter and collimator are less than that due to the HP camera.

Comparison of the mean inherent resolution index R_i (12 mm) of the Pho/Gamma III camera with bialkali phototubes (Table 1) with the R_s and R_g values listed in Table 2 shows that it exceeds the scatter component R_s at all depths studied and frequently exceeds the collimator component R_g, particularly at small depths. When the Pho/Gamma III camera with S-11 tubes is employed (mean $R_i = 17$ mm, from Table 1) it is the greatest contributor to overall system resolution loss at all depths studied, exceeding both scatter and collimator.

In conclusion, in typical clinical ^{99m}Tc imaging situations with a scattering medium present, the relative contributions of the gamma camera, collimator, and scatter to the measured total overall system resolution may be determined and have been presented for a selection of cameras, straight-bore collimators, and distances from each collimator face.

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