Collimator Evaluation for Tl-201 Myocardial Imaging

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Three collimators—high-resolution, converging, and pinhole—were evaluated for Tl-201 myocardial imaging. Line spread function, sensitivity measurements, and phantom and animal studies were used. Features common to all the collimators were: a) better resolution at a closer distance with higher count density, and b) higher infarct detection rate in the tangential projection than in the en face view relative to the lesion. Furthermore, an infarct in the epicardial location was better visualized than one in the endocardial location. In terms of resolution and sensitivity, the high-resolution collimator was found to be satisfactory in most clinical imagings, but for visualization of an infarct, its size by weight must be over 10–12 g. The pinhole collimator could resolve an infarct as small as 7 g, and use of the pinhole yielded a diagnostic accuracy of over 90%, compared with 75–80% for the high-resolution collimator. Although the low sensitivity of the pinhole collimator precludes its routine clinical use, the selected view would increase diagnostic accuracy. The converging collimator performed poorly in terms of lesion detectability, and its routine clinical use is not encouraged. The conclusion drawn here is valid in the system we have studied, but the variety of converging collimators must be evaluated further for their specific purposes.

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Since the introduction of Tl-201 for medical use (*1*), the low-energy high-resolution collimator (HRC) has been most commonly employed in both experimental and clinical myocardial studies (*2–8*). When the performance of the camera-collimator system was evaluated at a set distance (*9*), the low-energy converging collimator (CONV) has yielded the best line spread functions (LSF) and modulation transfer function as compared with the HRC and the 4,000-hole collimator. To date, however, relatively few investigators have used the CONV (*8,10*), and it has received no critical evaluation for myocardial imaging. Despite the fact that the superior resolution of the pinhole collimator (PHC) has been recognized in Tl-201 myocardial imaging (*11*), the PHC has been largely ignored for routine clinical use because of its poor sensitivity. Accordingly, we have evaluated three collimators with LSF, sensitivity measurements, and phantom and animal studies in order to determine the optimum collimation for Tl-201.

MATERIALS AND METHODS

Thallium-201 was produced by the $^{203}Tl(p,3n)$ $^{201}Pb \rightarrow {}^{201}Tl$ reaction. Maximum impurities at the end of the preparation were 0.1% Pb-201, 0.2% Pb-203, 2% Tl-200 and 0.5% Tl-202. The contamination was not significantly different from that previously reported (*1*). A scintillation camera* was used with the PHC, HRC, and CONV. On the basis of previous studies (*11*), a 5-mm aperture insert was used exclusively for the PHC. Converging collimation was obtained from the converging mode of a

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diverging-converging collimator (DIV-CON) designed primarily for Tc-99m.

The Tl-201 line source, 1.2 mm in diameter, was placed under the collimator at distances of 5 and 10 cm, measured from the collimator surface. At a 20% window setting for Hg x-rays, 100,000 counts were accumulated and stored in a dedicated minicomputer. The full width at half maximum (FWHM) of the LSF was then used as a measure of merit for each collimator at the two distances. The peak channel in the LSF had at least 5,000 counts, which gave a standard deviation of less than 2%. The procedure was repeated three times. No scattering medium was used for this evaluation.

The FWHM is a measure of resolution in a scintillation camera system, and a better resolution normally implies a narrower line-source image. However, the magnifying effect of the PHC makes the line-source image appear wider as the distance between the source and the PHC is reduced. In order to allow for this magnifying effect, the LSFs were stored in the minicomputer, along with an image of two lines spaced 5 cm apart. The FWHM was then measured in terms of channels in the computer, while the number of channels per centimeter at the source was calculated from the image of the double line source. The FWHM in units of channels was divided by the number of channels per centimeter to give a FWHM, in centimeters, that is independent of the magnification factor.

For the sensitivity measurement, the point source and the 6-cm-diameter disc source were loaded with equal activities of Tl-201 to obtain comparisons for each collimator and each source. The distances were 0, 5, 10, and 15 cm, and the measurement was repeated three times at each data point.

The phantom was made of thin-walled (2 mm) plexiglass with a simulated myocardial-wall thickness of 1.5 cm (Fig. 1). The simulated infarcts were of three different sizes. The 5- and 10-mm-thick lesions were used to represent either endocardial or epicardial infarcts; the 15-mm-thick lesion represented the transmural infarct. Images with the phantom were obtained in the anterior (en face) and lateral (tangential) projections at distances of 5 and 10 cm from the surface of the collimator. The total accumulated counts collected per image were 50,000, 100,000, 150,000, 300,000, and 500,000. Each image was then evaluated by three independent observers, who were asked to specify whether a simulated lesion was present or absent.

Based on the results of the phantom study, the CONV was eliminated from the animal studies. Infarcts were produced in 15 mongrel dogs (Nos. 1–15) by ligation of either the anterior descending or the circumflex coronary artery. Thallium-201 images were obtained in the 45° right anterior oblique, anterior, 45° left anterior oblique, and left lateral views, at 48 hr after ligation. For the PHC images, 200,000 counts were collected, and for the HRC images, 400,000 counts. All dogs were killed 24 hr after completion of the imaging procedure. In addition, Tl-201 images of five normal dogs (Nos. 16–20) with the PHC and HRC were included for interpretation. Three observers interpreted the images and recorded the presence or absence of infarction, and the location of the infarct if present.

The size of the infarct was determined in the following manner. The atria, free wall of the right ventricle, and any epicardial fat were removed. The aorta was removed at the level of the aortic valve. The left ventricle was then cut into slices about

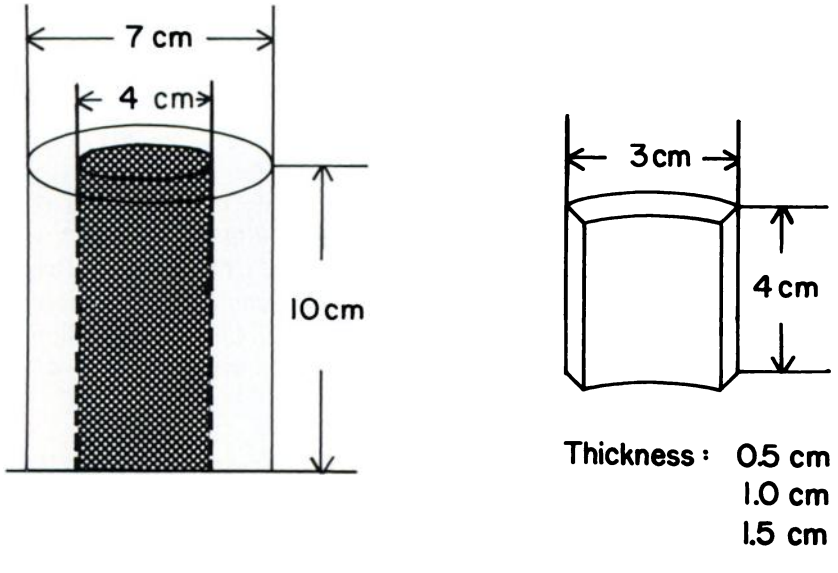

FIG. 1. Simulated lesions were constructed in three different sizes, and both medium-sized (10 mm thickness) and small (5 mm thickness) lesions were placed in either epicardial or endocardial location.

TABLE 1. LINE SPREAD FUNCTIONS USING Tl-201

Collimator	Distance (cm)	FWHM (cm)*
HRC	5	1.34 ± 0.01
HRC	10	1.57 ± 0.04
CONV	5	0.86 ± 0.01
CONV	10	1.58 ± 0.01
PHC†	5	0.37 ± 0.01
PHC†	10	0.71 ± 0.04

* ±1 s.d.
† 5-mm hole.

1 cm thick, in a direction parallel to the coronary sinus, and each slice was weighed. One or two giant histologic sections were made from each slice, at about the midportion, and stained with hematoxylin and eosin, and trichrome. Transparent grid paper was placed over each giant section, and the percentage of infarcted myocardium was determined. The weight of the infarcted myocardium in each slice was calculated, based on the percentage determined from the giant slices. Finally, the infarct weights from all the slices were added and the total expressed as a percentage of the left ventricle.

RESULTS

Results of the LSF analysis are shown in Table 1. The best resolution was seen with the PHC at both distances. Resolution at 5 cm was approximately twice as good as that at 10 cm. Similar results were obtained for the CONV, with resolution at the 5-cm distance almost the same as that for the PHC at 10 cm. With the HRC there was little difference in resolution between the two distances. The better resolution of the CONV, compared with the HRC, at 5 cm was not present at 10 cm. Thus, the sharp decline of resolution with increasing distance was characteristic of both PHC and CONV, but not for the HRC.

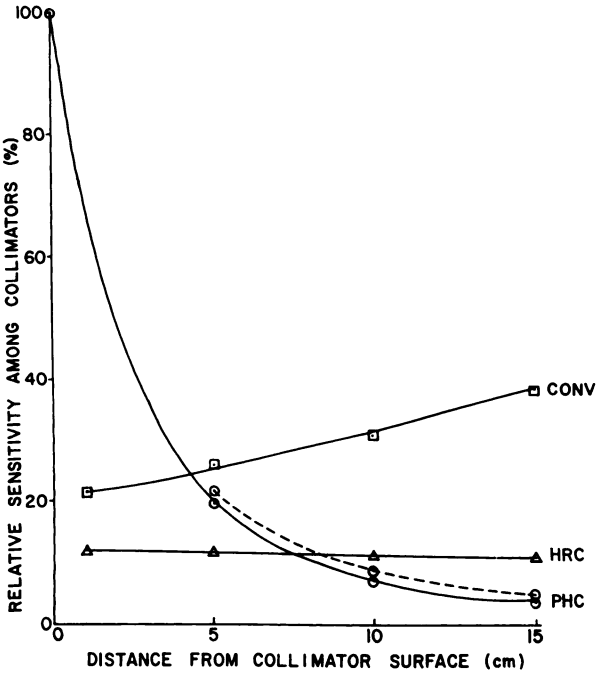

FIG. 2. Sensitivity as a function of distance. Dotted line indicates performance with disc source.

Figure 2 demonstrates the results of sensitivity measurements obtained with the three collimators. The point source and the disc differed in sensitivity by only 1–1.5% at each data point: higher for the disc source with the PHC and HRC, but lower for the disc source with the CONV. The sensitivity of the PHC decreased sharply with distance, and the reverse effect, though less striking, was seen with the CONV. In the case of the HRC, almost no difference was seen from 0- to 15-cm distance. Thus, in terms of sensitivity and resolution, the least distance effect was seen with the HRC, but both the PHC and CONV showed a rather marked distance effect: with the PHC, the closer the distance, the better the sensitivity and resolution, but whereas reduction of distance also improved the resolution of the CONV, it decreased the sensitivity.

The images were obtained for all possible combinations of the following parameters: five different accumulated counts per simulated lesion, two distances, anterior and lateral views, five combinations of size and location of the simulated lesions, and three collimators. These combinations resulted in 300 images to be evaluated ($5 \times 2 \times 2 \times 5 \times 3 = 300$). With all three collimators, images with 300,000 and 500,000 counts visualized all simulated lesions regardless of distance, view, size, or location. Furthermore, the largest simulated transmural infarct was always visualized under all conditions. Because the interpretations of these images were grossly obvious, they were not subjected to further evaluation by the observers. This reduced the final number of images to be evaluated to 144 ($3 \times 2 \times 2 \times 4 \times 3 = 144$).

In terms of lesion detection using the phantom, there was no significant difference between images containing 50,000–150,000 counts, despite the fact that clearer definition was generally achieved with higher counts, as shown in Fig. 3. Therefore, images containing 50,000, 100,000, and 150,000 counts were all combined for analysis. Table 2 shows the detection rates for the medium-sized lesion in two locations and at two distances. The epicardial lesion was visualized in all situations, but the endocardial lesion of the same size was better visualized in the

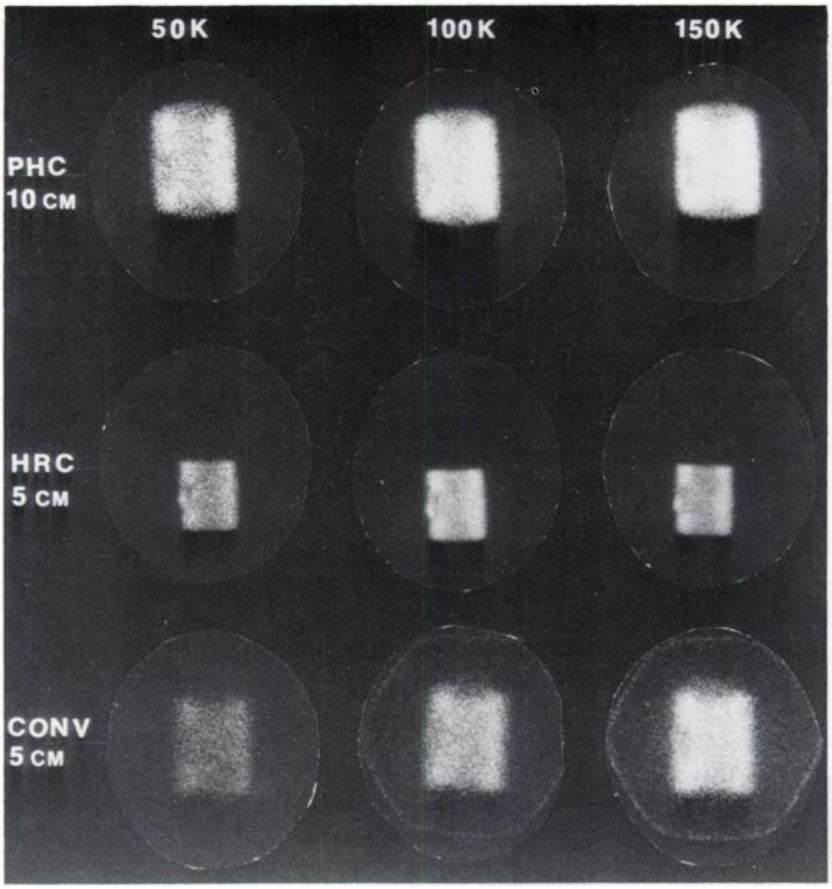

FIG. 3. Phantom images of medium-sized lesions in endocardial position are seen in lateral view. Relative magnification of images is proportional to original sizes.

lateral view than in the anterior view with all three collimators. No effect of distance on resolution was apparent with the PHC, but this was evident in the case of the CONV in both anterior and lateral views. The effect of distance with the HRC appeared to be less striking, as is suggested by the LSF.

As shown in Table 3, the small lesion was best seen by the PHC, which could resolve 20–30% of the endocardial lesions and 30–40% of the epicardial lesions in the lateral projection. The HRC could resolve the epicardial lesion only in the lateral view at the 5-cm distance; the small lesion was not seen by the CONV at either location or distance. There was no significant difference, however, between the HRC and CONV. As previously mentioned, given 300,000 or more counts per image, the small lesion was visible in all situations described here. Our earlier notion of the superiority of the CONV was not substantiated by the phantom study, and only the PHC and the HRC were used for the animal studies.

In these, a set of images consisted of four views each for the PHC and the HRC. This resulted in two sets of images per animal for 20 animals, giving a total of 40 sets. Since three independent observers participated in the evaluation, there were 120 readings for analysis. Table 4 shows the three individual performances in terms of correct and incorrect diagnosis. The overall accuracy of diagnosis in the sets of images was consistently higher with the PHC than with the HRC.

Individual instances of false-negative interpretations are shown in Table 5. Among the 15 dogs with infarcts, only four were subendocardial. The weight of these subendocardial infarcts ranged from 7 to 14 g, or 7–13% of the left-ventricular weight. The other 11 dogs had transmural infarcts with weights of over 22 g. With the HRC images, the infarcts in Dogs 6 and 9 were incorrectly read by all three observers, but each observer correctly identified the infarct in both dogs with the PHC images. On the other hand, Dog 7 had a transmural infarct of relatively good size by weight (28 g), but one observer missed the correct diagnosis using the HRC images. These data indicate that an infarct of less than 12 g can be missed entirely on the HRC images.

Figure 4 (Dog 9) illustrates a 7% anterior-wall infarct (apex region) that was not recognized by any of the three observers on the HRC images, but was seen by all three on the PHC images. Another example is shown in Fig. 5 (Dog 7), where a 24% infarct was missed by one reader on the HRC images, but was recognized with the PHC. These ex-

TABLE 2. DETECTION RATE (%) OF MEDIUM-SIZED LESION

	HRC		CONV		PHC	
Distance	5 cm	10 cm	5 cm	10 cm	5 cm	10 cm
Endocardium						
ANT	89	44	33	11	89	29
LAT	100	100	78	44	100	100
Epicardium						
ANT	100	100	100	100	100	100
LAT	100	100	100	100	100	100

TABLE 3. DETECTION RATE (%) OF SMALL-SIZED LESION

	HRC		CONV		PHC	
Distance	5 cm	10 cm	5 cm	10 cm	5 cm	10 cm
Endocardium						
ANT	0	0	0	0	11	0
LAT	0	0	0	0	33	22
Epicardium						
ANT	0	0	0	0	11	0
LAT	11	0	0	0	44	33

TABLE 4. DETECTION RATES (%) IN EXPERIMENTAL ANIMALS

Reader No.		True positive	False negative	True negative	False positive	Overall accuracy
1:	HRC:	80	20	100	0	85
	PHC:	93	7	80	20	90
2:	HRC:	73	27	100	0	80
	PHC:	100	0	100	0	100
3:	HRC:	80	20	60	40	75
	PHC:	100	0	80	20	95

TABLE 5. CASES WITH FALSE-NEGATIVE AND FALSE-POSITIVE READINGS

Dog No.	Infarct %	Infarct g	Location & type*	Collimator	False-negative (%)	False-positive (%)
1	13	14	Post SE	HRC	17	0
5	9	14	Ant SE	HRC	33	0
6	13	12	Post SE	HRC	50	0
7	24	28	Ant TM	HRC	17	0
9	7	7	Ant SE	HRC	50	0
16	0	0	— —	PHC	0	17
18	0	0	— —	PHC	0	17
19	0	0	— —	PHC	0	17
20	0	0	— —	PHC	0	17

* SE = subendocardial infarct
TM = transmural infarct.

amples illustrate the better delineation of the infarct by the PHC compared with the HRC.

On the basis of this study, we have concluded that the HRC should be used routinely for static imaging, and the PHC images should be added if the HRC images are not conclusive in terms of presence or absence of the infarct. Since our overall diagnostic accuracy was improved from 75–80% accuracy, based on the HRC images alone, to above 90% with the PHC, one or two additional views with the PHC may prove useful.

DISCUSSION

The resolution is better at the closer distance with all three collimators. However, a fair comparison of collimator performance cannot be made using the results of the LSF at a set distance alone, when the depth of the organ, its three-dimensional extension, and collimator characteristics are taken into consideration (*9*). In practice, the PHC is used at about 3–5 cm from the surface of the chest in the anterior view, as opposed to both the HRC and CONV which are used almost in contact with the chest wall. Furthermore, if the depth of the center of the heart is 5–7 cm from the chest wall, the result of the LSF at 10 cm for the PHC should be more fairly comparable with that of the 5 cm value for both HRC and CONV. However, the projected image of the heart cannot be directly extrapolated from the LSF at a set distance, since the LSF expresses only a two-dimensional effect, whereas the heart is a three-dimensional organ.

The image with the PHC or CONV is a readout whose features result from the complex mixture of relatively good resolution at the closer distance and of poorer resolution farther away. However, the resolution of the PHC is better than that of the CONV, and the resultant performance of the former is still superior. The least effect in this account is seen with the HRC; our data from the LSF indicate that distance has little effect on its resolution.

The field of view is a function of distance in the PHC and CONV, but not in the HRC (*12*). Inclusion of the heart in the field of view with the PHC necessitates a distance of 3–5 cm from the chest wall in the anterior view, but both the HRC and CONV can be placed as close to the chest wall as possible. Because of the different magnifying effects among the three collimators, the inclusion of the surrounding organs varies markedly, which is suggested in part by Fig. 3, and is shown clearly in Figs. 4 and 5. During imaging of the heart with the HRC and PHC, the size of the heart imaged by the latter is about five times that of the former. Consequently, the inclusion of the surrounding organs, all of which

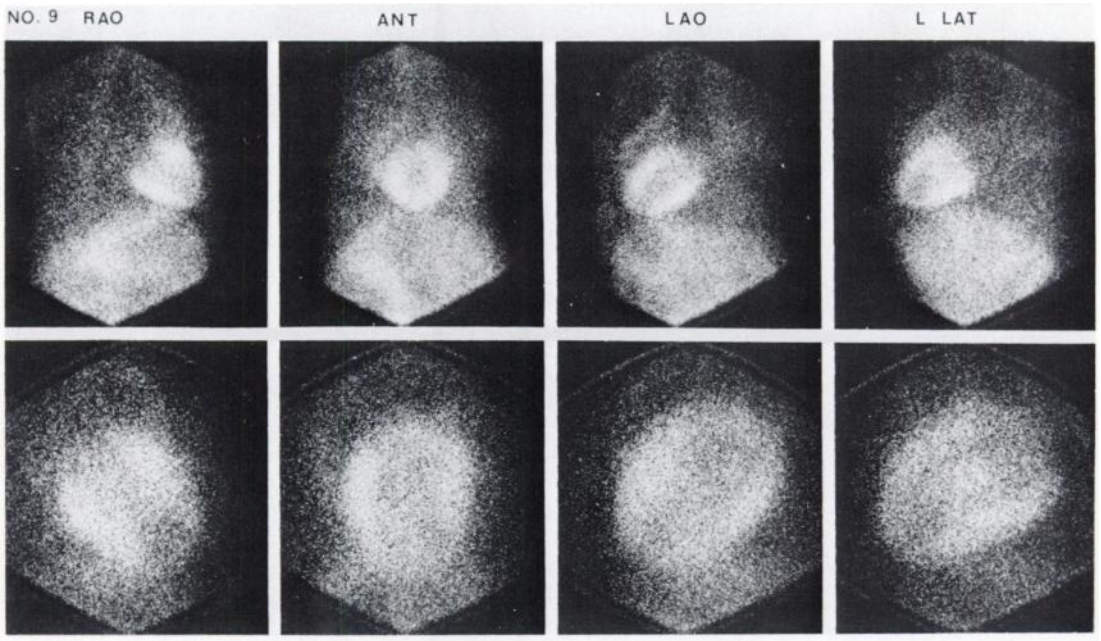

FIG. 4. Dog 9. Small infarct of 7% of left-ventricular wall in apical region was missed by HRC images (upper row). Defect is seen on lower portion of lateral wall just have apex in PHC image in anterior view (lower row).

contribute to the total counts collected for an image, varies depending upon the collimator and its positioning and distance relative to the patient. The HRC image with 400,000 counts takes about one-half the imaging time required by the PHC to collect 200,000 counts in the same projection. In other words, sensitivity measured by the point source can give an adequate comparison on theoretical grounds but not in clinical practice, since there is no way to assess the variable amounts of background activity.

Judicious use of the PHC must be emphasized, since its relatively low sensitivity can be detrimental. There is no need to use it routinely if the images obtained by the HRC are diagnostic. The PHC

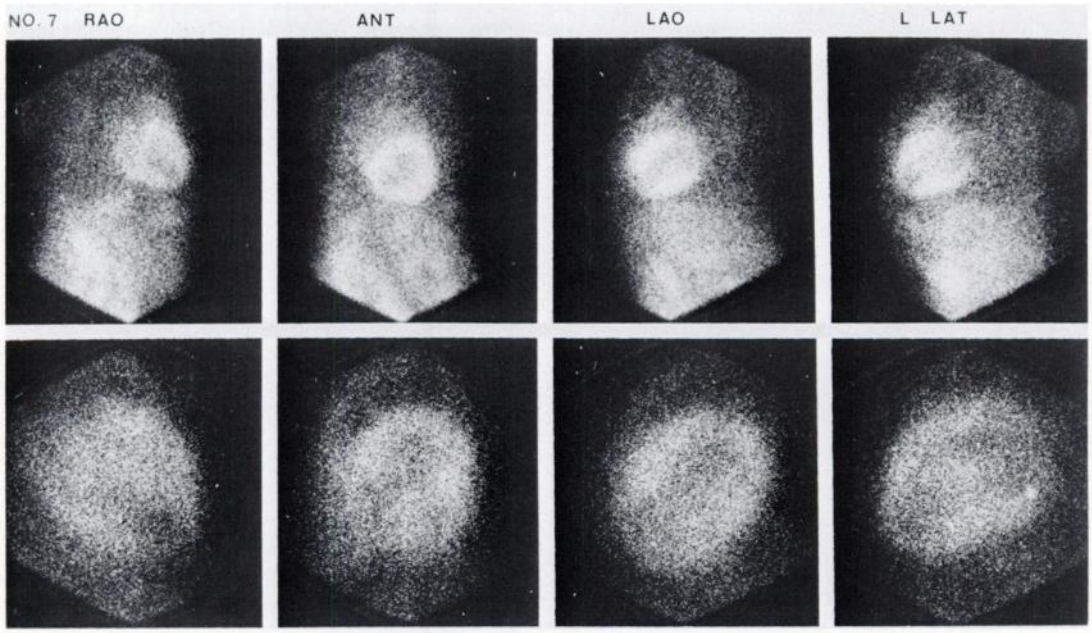

FIG. 5. Dog 7. Infarct involving 24% of left ventricle was difficult to appreciate in HRC images (upper row). Defect involves lower half of septum and apex; it can be seen faintly in HRC image, but is well defined by PHC images in anterior and left anterior oblique views (lower row).

should be utilized in cases where the HRC images are questionable and, further, when other clinical findings are suggestive of acute myocardial infarction. However, we must caution against faulty reading of PHC images of the apical region, where the myocardium is normally thinner; this can be misinterpreted as indicating an infarct as presented in our data.

Regardless of the collimator employed, we find that the tangential projection of the infarct would certainly improve diagnostic accuracy. The selection of a proper view in order to utilize the maximum effect of the collimator is particularly important when an additional PHC view is required. The appropriate PHC view can be chosen with ease, most of the time, by viewing the HRC images, thus optimizing the additional expenditure of time.

The routine use of the CONV for myocardial imaging was not encouraging when compared with the HRC and the PHC in this study. This conclusion must be read with caution since the result was contradictory to previous reports (*9,12*), where the specially designed 6,000-hole CONV yielded the best system performance compared with the HRC and the 4,000-hole collimator†. The CONV used in this study consisted of 12,000 holes and its performance was evaluated with the Series 100 camera. The different system performance could have arisen from the different designs of the two collimators and the different system capabilities of the two cameras. The advent of the large-field-of-view scintillation camera has given rise to a variety of converging collimators, and their performances vary a great deal depending upon the design (*13*). This trend appears to be true, to a lesser extent, for the standard scintillation camera, as well. For this reason, we are in no position to claim that the CONV is inferior for Tl-201 myocardial imaging, or that the combination of the Pho/Gamma HP and 6,000-hole CONV is unsuited for the study under the circumstance (*9*). We believe that the system performance of the individual CONV must be evaluated in terms of its intended use.

FOOTNOTES

* Ohio Nuclear Series 100.

† Pho/Gamma HP camera (Searle Radiographics), Des Plaines, Ill.

Mention of a commercial product does not constitute the endorsement of the product by the Bureau of Radiological Health, Food and Drug Administration.

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ERRATUM

The correct title of the article by T. Wang, R. Fawwaz, P. Esser, and P. Johnson appearing in *J Nucl Med* 19: 381-383, 1978 is "Altered Body Distribution of [^{99m}Tc] Pertechnetate in Iatrogenic Hyperaluminemia." In the same article, the second date in Table 1 should be 1/11/77 and the first line under the Discussion section should begin "These results show that..."