Physical Aspects of ^{99m}Tc, ^{87m}Sr and ^{18}F for Bone Scintigraphy

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SUMMARY

The physical properties of ^{99m}Tc, ^{87m}Sr and ^{18}F as bone scanning agents for a scintillation camera fitted with a medium energy diverging collimator, were determined. This was done by incorporating the plane source sensitivity, the modulation transfer function and the figure of merit. From the results it is clear that ^{99m}Tc is superior to ^{87m}Sr and ^{18}F.

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The clinical value of bone scintigraphy has been extensively proved.[1,2] The main limitation of the procedure is the long scanning time, as a result of the low photon yield of conventional radio-isotopes and poor sensitivity of scanning equipment. Recently, several radio-isotopes which render a low radiation dose to the patient and a higher photon yield, became available.[3-5] Polyphosphate,[6] and more recently diphosphonate, labelled with ^{99m}Tc in comparison with ^{87m}Sr-citrate, were investigated by us and the biological behaviour was found to be acceptable for bone scanning.

Since the physical properties of ^{87m}Sr and ^{18}F are not suitable for use with the gamma camera, the properties of ^{99m}Tc for bone scanning compared with ^{18}F and ^{87m}Sr were investigated. A medium energy diverging collimator was used during these investigations.

THEORY OF ANALYSIS

Radio-isotopes of interest in bone scanning were compared by utilising the modulation transfer function for geometrical resolution and the figure of merit introduced by Beck and Harper[7] to evaluate the over-all imaging properties of these isotopes. These measurements were performed at 2-cm intervals in a tissue-equivalent scattering medium.

The use of the figure of merit to evaluate the radio-isotopes is essential, since the sensitivity of the gamma camera and the photon yield for each radio-isotope is an important factor in the over-all resolution that can be obtained. The figure of merit is given by: $Q(\nu) = 2\overline{C}\, M(\nu)^2$ where $Q(\nu)$ is the figure of merit, $M(\nu)$ the modulation transfer function and $\overline{C}$ the plane source sensitivity or the average count rate of a plane source given by $\overline{C} = R/S$, where R is the count rate density in counts $\text{min}^{-1}\ \text{cm}^{-2}$ and S is the specific activity in $\mu\text{Ci cm}^{-2}$. By introducing the unit specific activity in the calculation of the figure of merit, different radio-isotopes can be evaluated in terms of radioactivity.

In the preliminary clinical investigation of ^{87m}Sr compared with ^{99m}Tc-polyphosphate as a bone scanning agent, it was found that although the target to non-target count rate ratio of the ^{99m}Tc compound was not increased, images of higher quality were obtained simply because of the higher photon sensitivity from ^{99m}Tc used with the gamma camera. By using the figure of merit as described, the qualitative information obtained from the preliminary clinical investigation can be quantitatively verified. For the determination of the figure of merit, the modulation transfer function was calculated from the line source response function, obtained at various depths in a scattering medium. The computer programme obtained from the IAEA for the calculation of the modulation transfer function was used, and extended to calculate the figure of merit using the plane source sensitivity. The computer programme was further modified to plot the line source response function, modulation transfer function and figure of merit by the use of a line printer. This programme was run on an ICL-1900 computer.

METHODS

Radio-isotopes

The radio-isotopes used were ^{87m}Sr, ^{99m}Tc and ^{18}F. The radiation dose to the patient in bone scanning from these isotopes, compared with the more conventional isotopes such as ^{85}Sr, is low.[8] The physical properties of the radio-isotopes are summarised in Table I. ^{87m}Sr and ^{99m}Tc are commercially available (Philips Duphar, Holland), while ^{18}F was obtained from the National Physical Research Laboratories in Pretoria.[9]

A Nuclear Chicago Pho/Gamma III scintillation camera was used for the investigation, and an energy window of 20% was adjusted over the photopeak.

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TABLE I. PHYSICAL PROPERTIES OF THE ISOTOPES[5,13,14]

				Radiation dose (mrad/mCi)		
Isotope	Half-life	γ-energy (MeV)	Photons/ disintegration	Average whole body	Skeletal	Bone marrow
^{99m}Tc-diphosphonate or polyphosphate	6,0 h	0,140	0,90	11	45	10
^{87m}Sr	2,8 h	0,389	0,79	20	160	20
^{85}Sr	64 d	0,513	1,00	13 000	55 000	—
^{18}F	1,87 h	0,511	1,94	50	290	40

Experimental Method

Measurement of plane sensitivity at various depths: A known activity of radio-isotope was placed in a plane source and the sensitivity measured at 2-cm intervals in tissue-equivalent scattering medium up to a depth of 14 cm. The sensitivities at these depths were obtained by the use of an electronic window of 1 cm^2. The region of interest was small compared with the source area, and the influence of the inverse square law was therefore excluded. From these sensitivity measurements, attenuation curves and the half-value thickness for each radio-isotope were obtained.

Measurement of the line spread function: The line spread function was also measured in a scattering medium at the same depths as the plane source by means of a 144-channel analyser. The X-co-ordinate output pulses from the gamma camera were digitised and analysed. Each channel represented a spatial distance of approximately 1 mm. The data accumulated in the analyser were printed to be punched for further computation.

RESULTS

Plane Sensitivity

From the results summarised in Table II, it is clear that the efficiency for ^{87m}Sr is much lower than that of ^{99m}Tc. The sensitivity of ^{18}F is of the same order of magnitude as that of ^{99m}Tc, despite the low inherent sensitivity of the gamma camera. The high sensitivity of ^{18}F is probably due to the high gamma photon yield as a result of positron decay and septal penetration.

The half-value thicknesses obtained for the various radio-isotopes are very similar.

Geometrical Resolution

Fig. 1 (a and b) illustrates the line source response curves at depths of 0 cm and 6 cm from the collimator face. As a result of septal penetration, the resolution with ^{18}F is inferior to that of ^{87m}Sr and ^{99m}Tc. The effect of septal penetration can be seen clearly in the widening of the Gauss-shaped curves. The deterioration in resolution can be roughly expressed as the full width at half maximum, and these values are shown in Fig. 2 (a). The full width at three-tenths maximum emphasises the resolution deterioration as a result of septal penetration (Fig. 2 b).

TABLE II. PLANE SENSITIVITY

Isotope	Plane sensitivity (counts min^{-1} μCi^{-1})	Half-value thickness (cm)
^{99m}Tc	146	5,8
^{87m}Sr	52	6,3
^{18}F	150	6,8

The modulation transfer function calculated from these line response curves at the surface and at a depth of 6 cm are shown in Fig. 3 (a and b). The geometrical resolution obtained with ^{18}F is poor in comparison with ^{87m}Sr and ^{99m}Tc.

The Siemens Star pattern can also be used to visualise the geometrical resolution that can be obtained with the isotopes ^{99m}Tc, ^{87m}Sr and ^{18}F. The alternative compartments of the pie-shaped phantom were filled with each of the isotopes to obtain a scintigram. For each scintigram 100 000 counts were accumulated at the surface and at 6-cm depth in a scattering medium. The results are illustrated in Fig. 4. Scintigrams (a), (b) and (c) were obtained with ^{99m}Tc, ^{87m}Sr and ^{18}F, respectively. The upper scintigrams were obtained at the surface and the lower scintigrams at 6-cm depth. These scintigrams depict the inferior geometrical resolution obtained with ^{18}F in comparison with ^{87m}Sr and ^{99m}Tc.

Over-all Resolution

The results of the over-all resolution calculated from the plane source sensitivity and line source response on the surface, and at a depth of 6 cm in tissue-equivalent scattering medium, are shown in Fig. 5. The approximate tumour-diameter equals half the inverse of the frequency. At 0-cm depth (Fig. 5 a) and frequency 0,07 c/cm or larger, ^{99m}Tc becomes superior to the other two isotopes for tumour diameters of 7 cm or smaller. At 6-cm depth (Fig. 5 (b) ^{99m}Tc is superior as soon as the frequency increases above 0,1 c/cm, which corresponds to tumour diameters of 5 cm or smaller.

From these figures it is clear that the over-all resolution with ^{87m}Sr and ^{18}F is much inferior to that of ^{99m}Tc especially when tumours in the order of 2-cm diameter need to be detected. It is obvious from these results that the geometrical resolution of ^{18}F is the main cause for the image deterioration. A better resolution could probably have been obtained with a pinhole collimator, but dis-

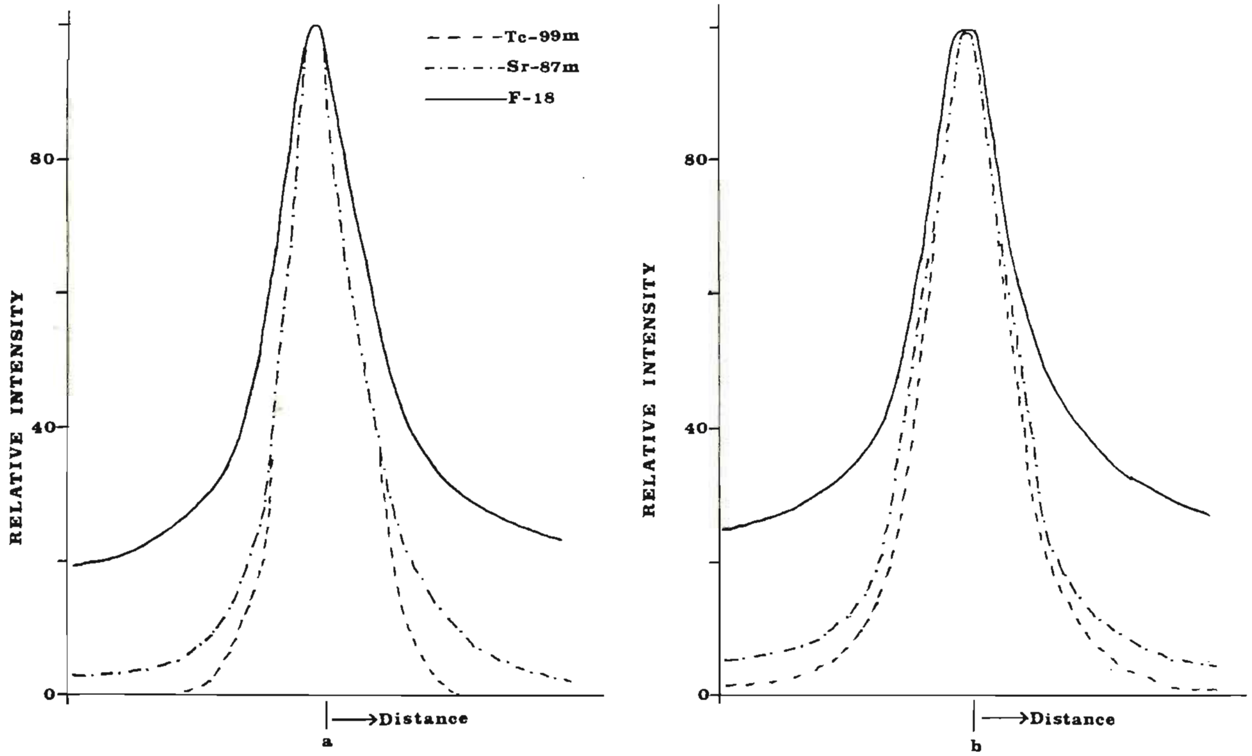

Fig. 1. Line source response curves at (a) 0 cm and (b) 6 cm from collimator face.

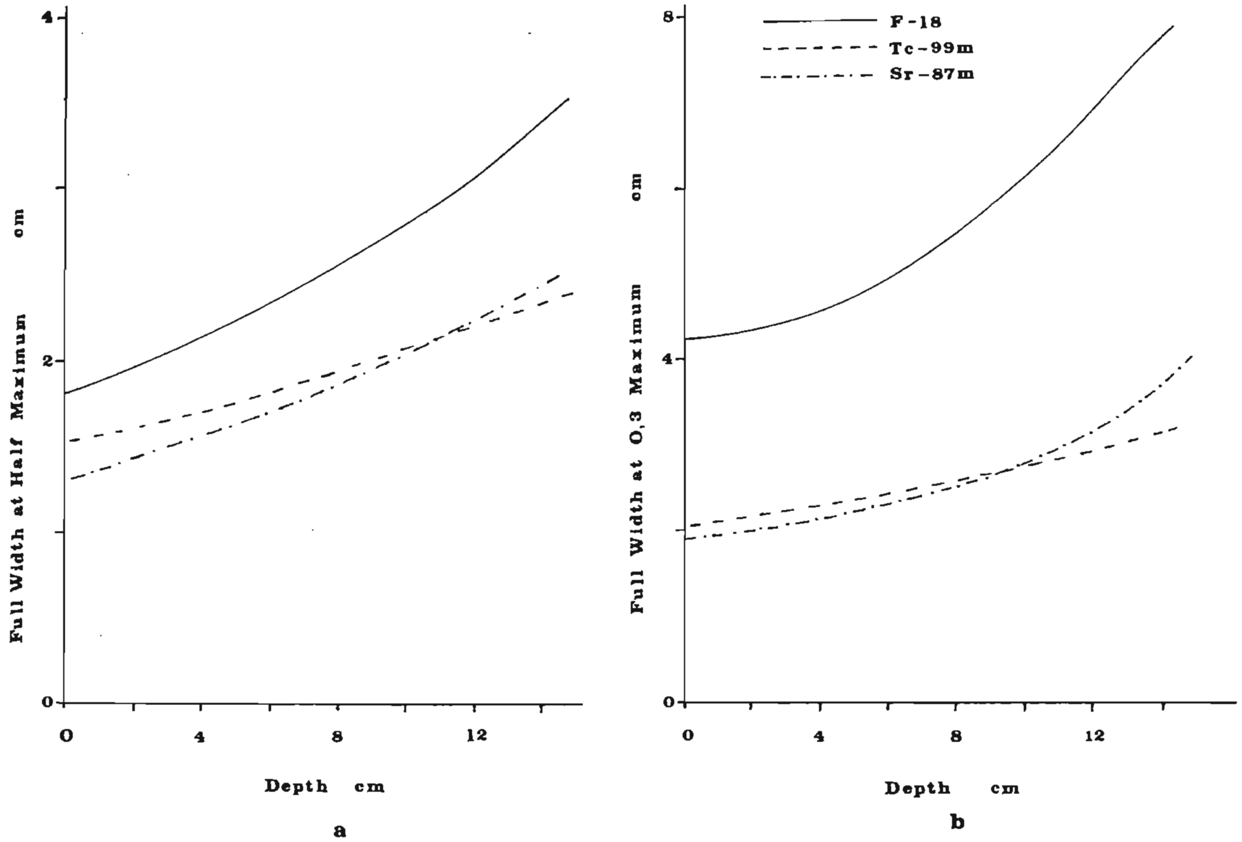

Fig. 2. Curves of (a) full width at half maximum and (b) full width at three-tenths maximum at various distances from the collimator face in a scattering medium.

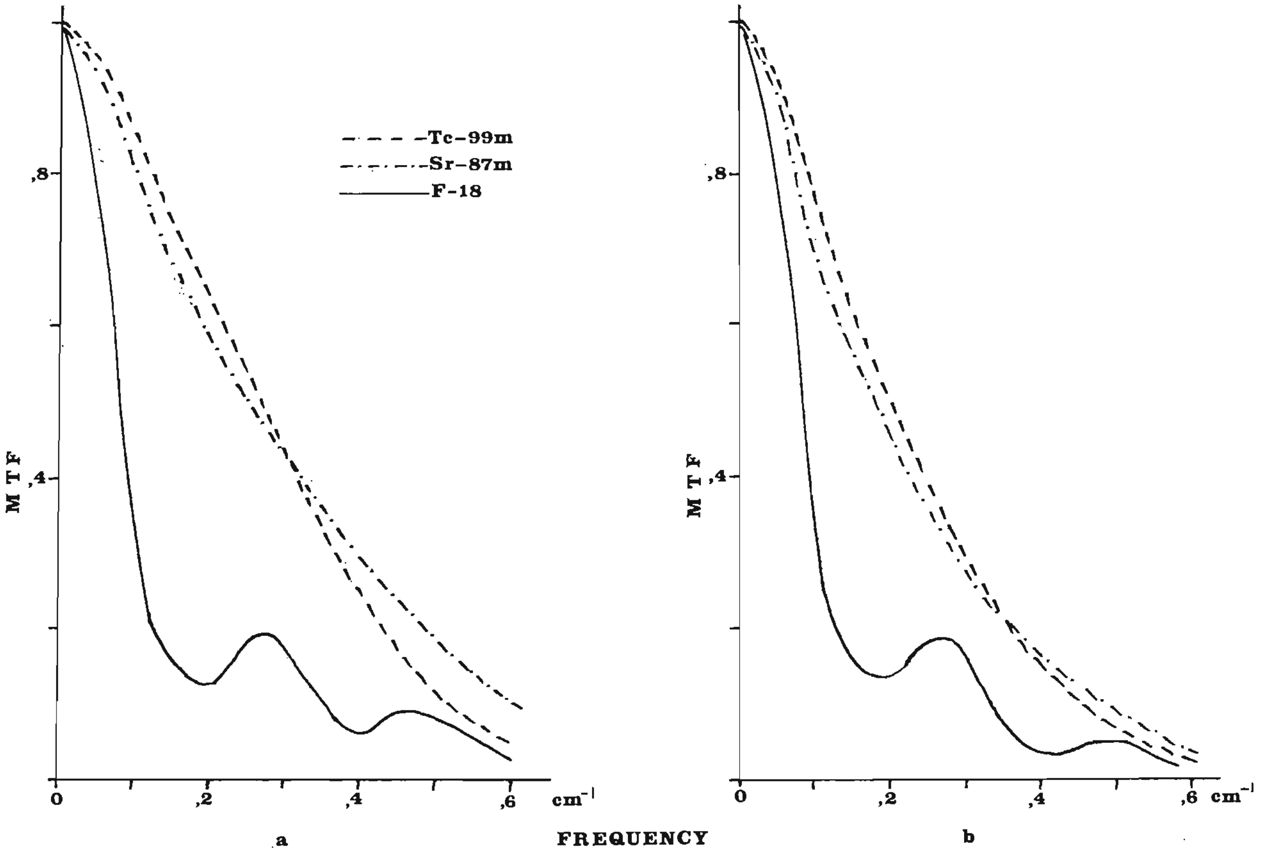

Fig. 3. Modulation transfer function for (a) 0 cm and (b) 6 cm in tissue-equivalent scattering medium.

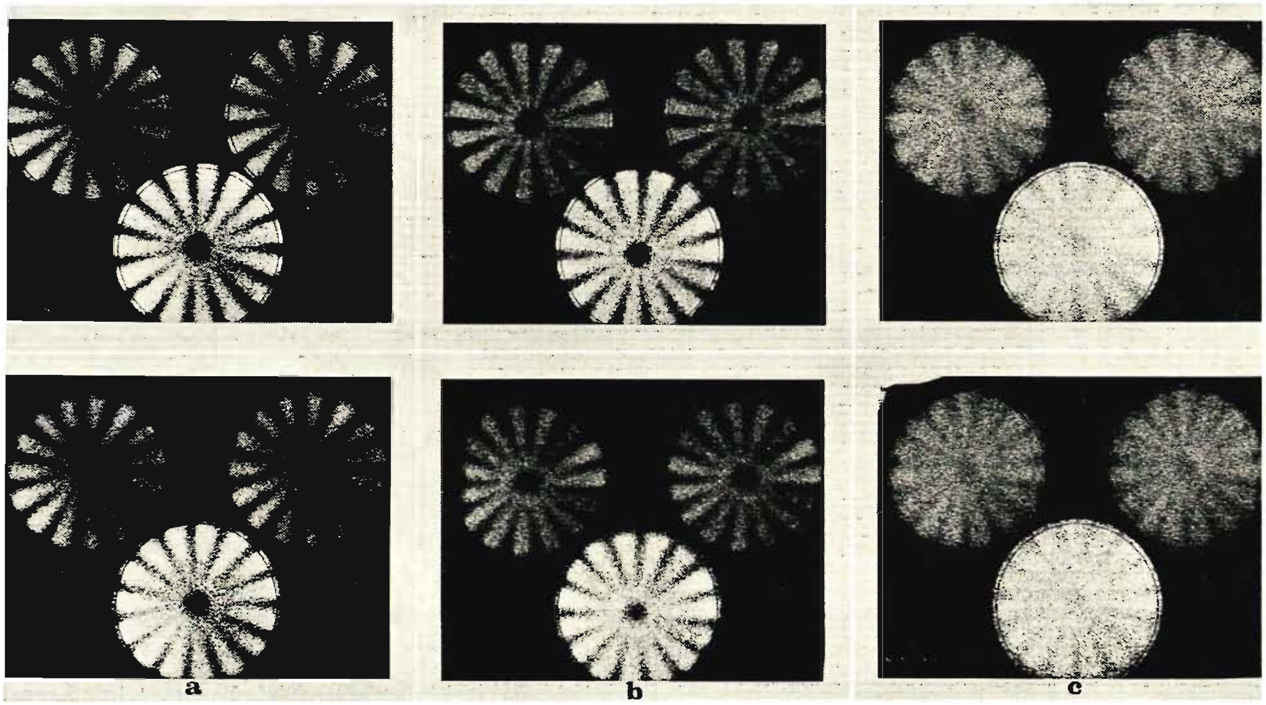

Fig. 4. Siemens Star pattern for (a) ^{99m}Tc, (b) ^{87m}Sr and (c) ^{18}F. Upper images were obtained at the collimator face and lower images at 6 cm depth in a scattering medium.

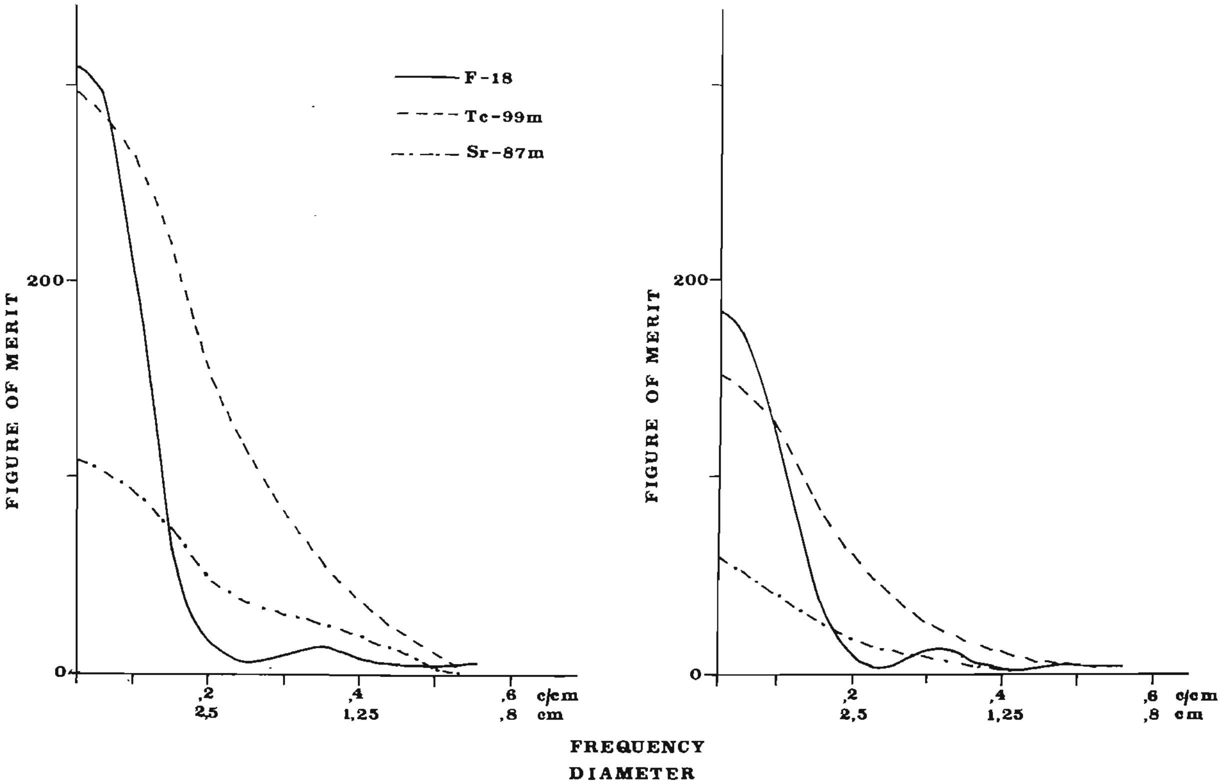

Fig. 5. Figure of merit curves as a function of frequency and tumour diameter at (a) 0-cm and (b) 6-cm depth.

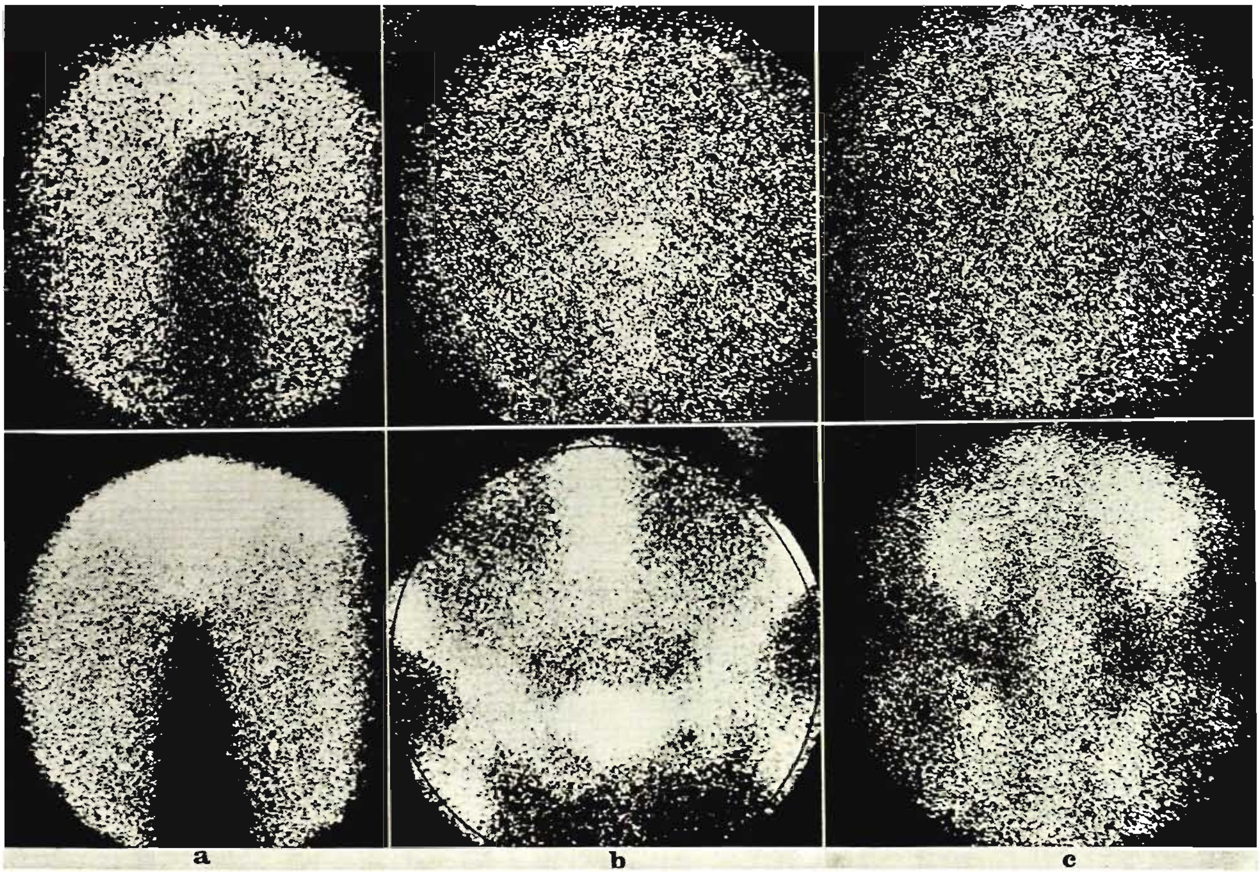

Fig. 6. Comparative bone scans of identical regions in the same patients. Above: **with ^{87m}Sr-citrate;** below: **with ^{99m}Tc-polyphosphate — (a) femur, (b) pelvis and (c) lumbar vertebrae.**

uniformities and poor sensitivity make the over-all resolution even worse.[10-12]

The higher sensitivity of ^{99m}Tc compared with that of ^{87m}Sr results in a better over-all resolution. The influence of the sensitivity on clinical scintigrams is illustrated in Fig. 6. The upper scintigrams were obtained with ^{87m}Sr-citrate and the lower scintigrams with ^{99m}Tc-polyphosphate. The increased over-all resolution obtained with ^{99m}Tc compared with ^{87m}Sr as a result of increased sensitivity, is clearly demonstrated.

Furthermore, the diverging collimator is designed specifically for medium energy photon range, and should a low-energy collimator be used, the efficiency for ^{99m}Tc could be increased by a factor of two or more.

DISCUSSION

^{99m}Tc-labelled diphosphonate and polyphosphate are more economical and easier to use than the short-lived ^{18}F. ^{99m}Tc generators are generally available in all nuclear medicine laboratories, which is not the case with ^{87m}Sr generators.

The investigation emphasises previous clinical results of degradation due to the high energy photons. Despite favourable biological behaviour and physical properties, such as high photon yield and short half-life, the low inherent sensitivity and poor resolution render ^{18}F unsuitable for the gamma camera.

Whole-body images are essential in bone scintigraphy. This normally results in a long imaging time, which can be considerably reduced with the use of a ^{99m}Tc-labelled bone scanning agent.

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REFERENCES

1. De Nardo, G. L. and Volpe, J. A. (1966): J. Nucl. Med., **7**, 219.
2. Faber, D. D., Wahman, G. E., Bailey, T. A., Flocks, R. H., Culp, D. A. and Morrison, R. T. (1967): J. Urol., **97**, 526.
3. Hosain, F., Hosain, P., Wagner, H. N. jun., Dunson, G. L. and Stevenson, J. S. (1973): J. Nucl. Med., **14**, 410.
4. Ackerhalt, R. E., Blau, M., Bakshi, S. and Sondel, J. A. (1973): *Ibid.*, **14**, 375.
5. Bok, B., Perez, R., Panneciere, C. and Di Paola, R. (1973): *Ibid.*, **14**, 380.
6. Anderson, J. D., Iturralde, M., Lötter, M. G. and Minnaar, P. C. (1973): S. Afr. Med. J., **47**, 2468.
7. Beck, R. N. and Harper, P. V. (1968): *Fundamental Problems in Scanning*, p. 348. Springfield: Charles C. Thomas.
8. Pendergrass, H. P., Potsaid, M. S. and Castronovo, F. P. (1973): Radiology, **107**, 557.
9. Shepstone, B. J., Blake, K. C. H., Hering, E. R. and Steyn, J. A. (1973): S. Afr. Med. J., **47**, 1060.
10. Brookeman, V. A. and Bauer, T. J. (1973): J. Nucl. Med., **14**, 21.
11. Fink, D. W. and Wilcox, F. W. (1972): *Ibid.*, **13**, 338.
12. Moyer, R. A. (1973): *Ibid.*, **14**, 432.
13. Smith, E. M., Brownell, G. L. and Ellett, W. H. (1968): *Principles of Nuclear Medicine*, p. 763. Philadelphia: W. B. Saunders.
14. Spencer, R., Herbert, R., Rish, M. V. and Little, W. A. (1971): Brit. J. Radiol., **44**, 984.