Maximum-Likelihood Reconstruction with Ordered Subsets in Bone SPECT

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This study was aimed at determining whether the ordered-subset expectation maximum (OSEM) is more effective than filtered backprojection (FBP) for bone SPECT in the routine clinical context. **Methods.** Fifty-seven consecutive bone SPECT studies were analyzed. They included pelvic and lumbar spine, thoracolumbar spine, head and neck, feet and shoulders. A 64-projection SPECT study was acquired over 360° by single-head cameras 2–3 h after the injection of 750 MBq ^{99m}Tc-methylene diphosphonate. Three observers compared the OSEM and FBP reconstructed images. **Results.** Streak artifacts, always present with FBP, were rarely generated with the OSEM. When present (n = 24), artifacts associated with negative values near hyperactivities in FBP were not generated with the OSEM in 67% of the cases (n = 16), permitting a satisfactory interpretation of these regions. In half of the other cases (17%, n = 4/24), interpretation was precluded. In only one case did the three observers agree that more hyperactivities were seen with the OSEM. Ninety-six percent of the OSEM pictures were superior or equal to FBP for anatomic resolution and were clearly better in 12% of the cases. The extent of the lesion with the OSEM seemed better or equally defined in 96% and clearly better in 14% of the cases. The low-activity regions were better or equally visualized in all cases and were clearly better seen in 23% of the cases. The quality of the pictures was found to be better or superior with the OSEM in 98% of the cases and definitely better in 65% of the cases. **Conclusion:** Replacement of FBP by the OSEM in bone SPECT would be beneficial to clinical practice.

Key Words: bone SPECT; filtered backprojection; iterative reconstruction; maximum likelihood of expectation maximization; ordered-subset expectation maximum

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In the routine clinical context, filtered backprojection (FBP) has been for many years the only reconstruction method applied to bone SPECT. In addition to the loss of resolution associated with the filter and the difficulty in choosing the more appropriate filter (*1,2*), FBP may generate artifacts, mainly streaking artifacts and negative values (*3–6*) near the border of intense hyperactivities. In SPECT of the pelvis, the artifacts originating from the bladder activity may partially or totally obscure the hips (*4,7,8*). Highly active kidneys are a frequent problem in SPECT studies of the lumbar spine. In articulations, the nonpathologic surrounding may be partially masked by the streak artifact centered on the areas of hyperactivities and the negative values in the vicinity of these hyperactivities.

The maximum likelihood of expectation maximization (MLEM) algorithm does not suffer these limitations. No filter must be chosen. The reconstructed spatial resolution is better than that achieved with only ramp-FBP for an equivalent noise level (*9*). The streak artifacts should not appear, and the positivity (absence of negative values) of the reconstruction is guaranteed (*3,6,10*). Finally, the algorithm converges (*3,10*), but slowly (*6,11*). The major drawback of the method is the high number of iterations that are required. Indeed, the higher the number of iterations, the higher the noise level (*9,12*). Therefore, stopping rules must be defined either by limitation of the iteration number or by use of an a priori constraint (*6,9,13*). The MLEM has been widely studied theoretically and on phantoms. To our knowledge, the MLEM has been rarely used in clinical research, probably because of the powerful computer system needed (*6*). However, present-day workstations are able to perform this kind of processing in a relatively short time. The use of the ordered subsets (OS) accelerating procedure further shortens the reconstruction time (*6*).

The aim of this study was to determine whether the fast iterative reconstruction method, the ordered-subset expectation maximum (OSEM), is more effective, essentially from a qualitative point of view, than classical FBP for bone SPECT in the routine clinical context.

MATERIALS AND METHODS

Materials

From 15 June to 30 September 1997, 57 consecutive bone SPECT studies were analyzed. All patients referred to this department for bone SPECT were included in the study. The regions of interest were the pelvic and lumbar spine (n = 48), the thoracolumbar spine (n = 4), the head and the neck (n = 3), the feet (n = 1) and the shoulders (n = 1).

Methods

For each patient, a whole-body scan was acquired 2–3 h after injection of 750 MBq ^{99m}Tc-methylene diphosphonate, followed by 64-projection (20 s per projection) tomography over 360° in a 64 × 64 format. This acquisition protocol follows the recommendations of the Society of Nuclear Medicine (*14*). Single-head cameras were used: Sophy DSX (Sopha Medical Vision, Buc, France) and

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General Electric AC400 (General Electric Medical Systems, Milwaukee, WI). The Sophy camera was equipped with the low-energy, ultra-high-resolution collimator, and an electronic zoom of 8/6 provided a pixel size of 6.9 mm. The General Electric camera had a low-energy, high-resolution collimator, and the pixel size was 6.4 mm. The resolution at 10 cm (full width at half maximum for a point source in air) was 6.5 ± 0.3 mm for the Sophy system and 8.0 ± 0.3 mm for the General Electric camera. Both systems had almost identical sensitivities of 5.0 ± 0.5 cpm/kBq.

FBP reconstruction was performed using Vision software (SMV). A Hanning filter with a cutoff frequency of 0.5 cycle/pixel was applied in the course of the backprojection.

The iterative reconstruction algorithm was the OSEM implemented as a two-dimensional reconstruction. Neither attenuation correction or resolution recovery was attempted. Two iterations were applied to eight subsets. This subset–iteration combination gave visually the best images. For the 64 transverse slices, the reconstruction time was 3 s for FBP and 14 s for the OSEM on an RISC 6000 3AT workstation (International Business Machines, White Plains, NY).

All acquisitions were reconstructed by both methods (i.e., FBP and OSEM). None of the reconstructions was postfiltered. Transverse, coronal and sagittal slices were displayed with a gray scale and printed on black background.

Analysis of Results

The 57 SPECT studies were submitted to visual analysis by three observers. The paired reconstructions were randomized, and the method of reconstruction was not indicated. Two of the observers had experience with FBP and OSEM pictures; the other observer had experience with only FBP pictures.

The observers compared FBP and OSEM pictures for different criteria: presence and extent of streak and negative-value artifacts near hyperactivities, number of lesions, definition (anatomic definition, lesion extent and visualization of low-activity regions) and quality of the pictures (general impression).

RESULTS

Results are presented regardless of the anatomic regions examined because they are not influenced by topography.

Artifacts

Streak artifacts, which are always present with FBP, were rarely generated with the OSEM (Fig. 1 and Table 1). A paravenous injection in each of two patients who were unable to raise their arms caused significant FBP streak artifacts that were less intense in the OSEM pictures (Figs. 2 and 3).

When present (n = 24), artifacts associated with negative values near hyperactive regions were not generated or only minimally generated by the OSEM in 67% (n = 16) of the cases, permitting a satisfactory interpretation of these regions (Figs. 3 and 4). However, in 33% (n = 8) of the cases, OSEM provided unsatisfactory images. In half of these cases (17%, n = 4), interpretation was impossible (Fig. 2).

Number of Lesions

The three observers agreed in only one case on the presence of an additional hyperactivity on the OSEM picture (Fig. 5 and Table 2).

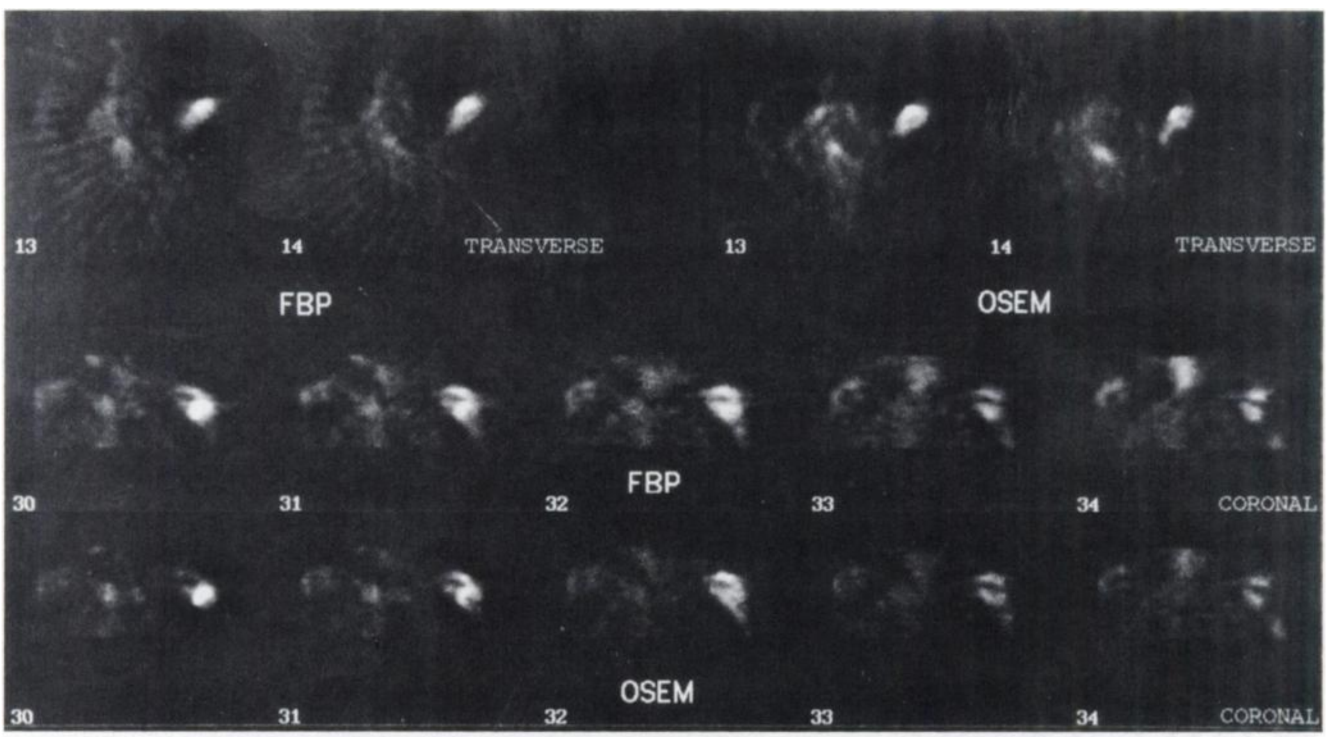

FIGURE 1. The only shoulder SPECT study performed in this series was blurred by streak artifacts generated by filtered backprojection (FBP) reconstruction technique, but these artifacts were not present with ordered-subset expectation maximum (OSEM). Resolution seems to be inferior with FBP.

TABLE 1
Common Artifacts Generated by FBP Reconstruction Method

Artifact or negative value	Generation	No. of lesions	%
Streak artifacts	Not generated by OSEM when present in FBP (n = 57)	57/57	100
	Still present with OSEM	0/57	0
Negative values added near hyperactivities	Not generated or minimally generated by OSEM (interpretable) when present in FBP (n = 24)	16/24	66.6
	Also generated by OSEM		
	Found uninterpretable by 2/3 of observers	4/24	16.7
	Found interpretable by 2/3 of observers	4/24	16.7

FBP = filtered backprojection; OSEM = ordered-subset expectation maximum.

All streak artifacts and most negative values were not observed in OSEM pictures.

Definition

Ninety-six percent of the OSEM pictures were superior or equal to FBP for anatomic definition (Table 3). Moreover, in 12% of the pictures, all observers agreed that the anatomic definition with the OSEM was clearly better.

The lesion area with the OSEM seemed to be inferior or equal to FBP in 96% of the cases. It was obviously inferior in 14% of the cases (Fig. 6). The low-activity regions were better visualized or equally visualized in all cases and clearly were better seen in 23% of the cases.

General Impression

The quality of the pictures obtained was better or identical with the OSEM than with FBP in 98% of the cases (Table 4). The quality was definitely better with the OSEM in 65% of the cases (Figs. 1, 2 and 4).

DISCUSSION

In this study, FBP is state of the art in routine clinical bone SPECT. The filter used in FBP remains the user's choice; the Hanning filter is used routinely for bone SPECT at this institution. Because this filter is popular and is available in virtually all commercial software, we used it in this study.

The number of subsets and the number of iterations must be set with the OSEM technique. Recommendations for the subset number can be found in previous studies (*6,11*) and are summarized as follows. Use the highest number of

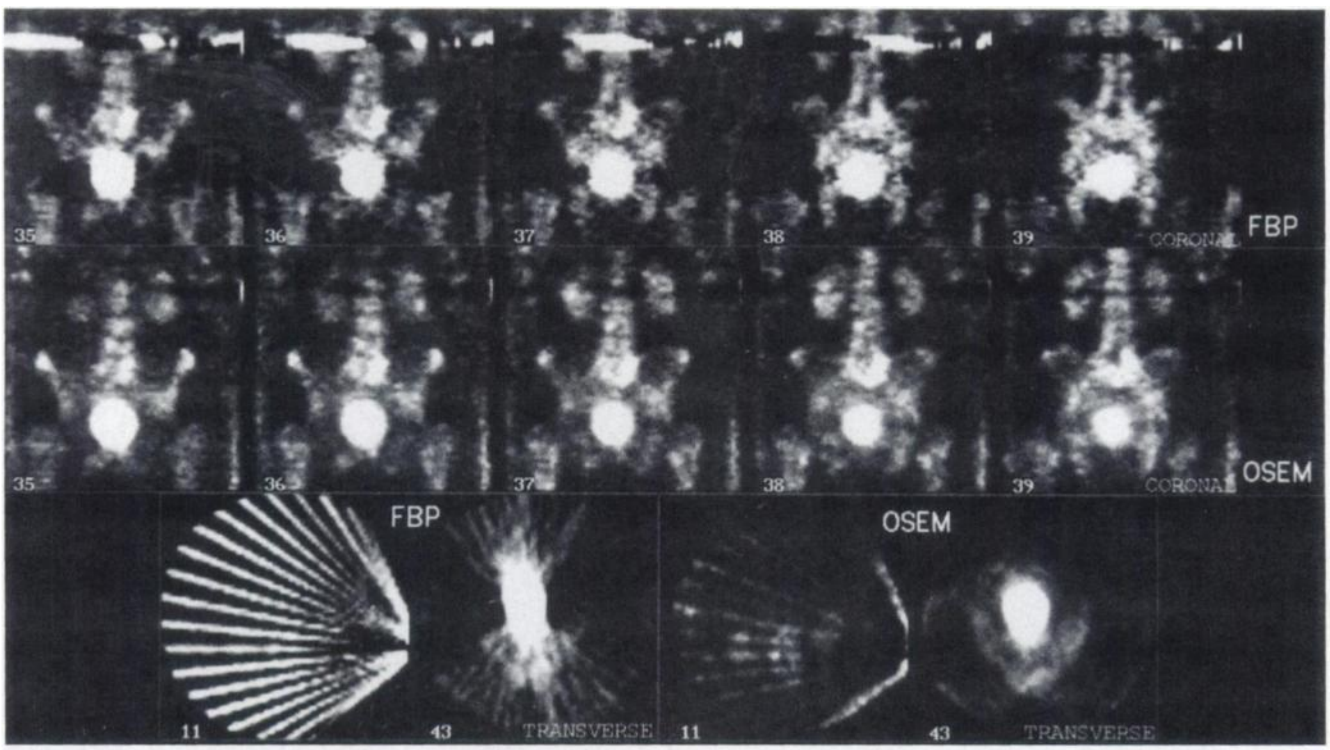

FIGURE 2. Important artifacts were generated by filtered backprojection (FBP) after reconstruction of pelvic and lumbar SPECT images in patient with paravenous injection in left arm, which entailed low statistics counting. Patient was not able to raise the arms and presented with important bladder residual activity. Ordered-subset expectation maximum (OSEM) helped with both artifacts, erasing L1 (paravenous injection, transverse slice 11) and erasing both hips (bladder activity, transverse slice 43). Images remained unsatisfactory, but general outlook improved with OSEM.

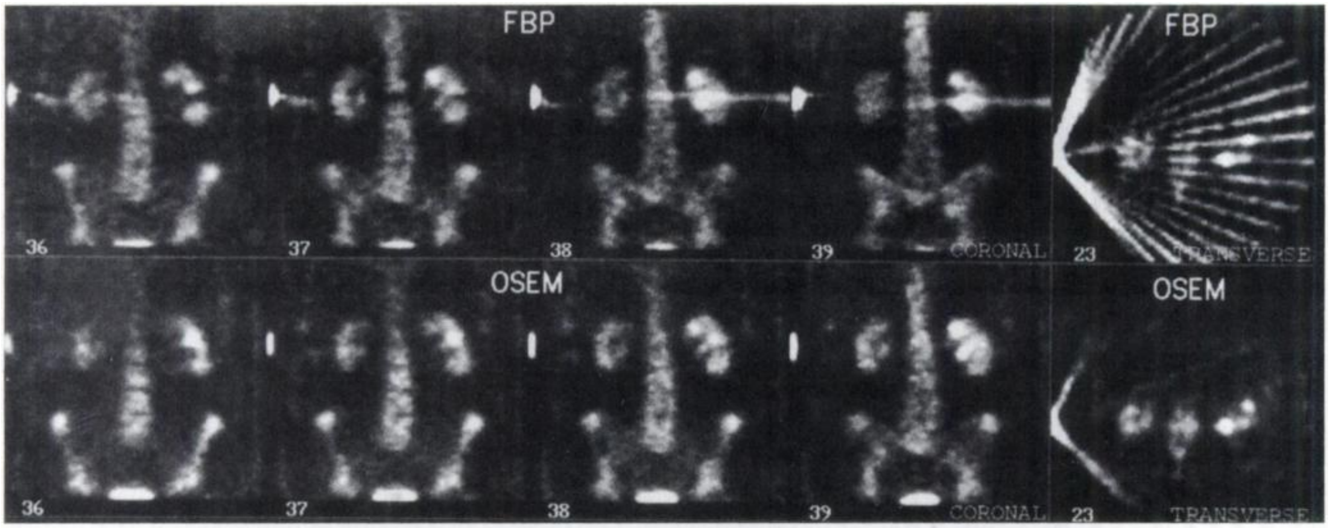

FIGURE 3. Second patient with paravenous injection of tracer was unable to raise the arms. With ordered-subset expectation maximum (OSEM), streak artifact was of lower intensity than with filtered backprojection (FBP), making examination interpretable.

subsets while keeping at least 4 projections per subset. The higher the subset number, the more enhanced the reconstruction speed. Below 4 projections per subset, significant differences could arise between MLEM and OSEM reconstructions (*15*).

With eight subsets and 64 projections, all subsets contain 8 projections. In this way, we are not too close to the limit of 4 projections per subset, and the reconstruction time is divided by 8 in comparison with the MLEM. Once the number of subsets is chosen, the number of iterations

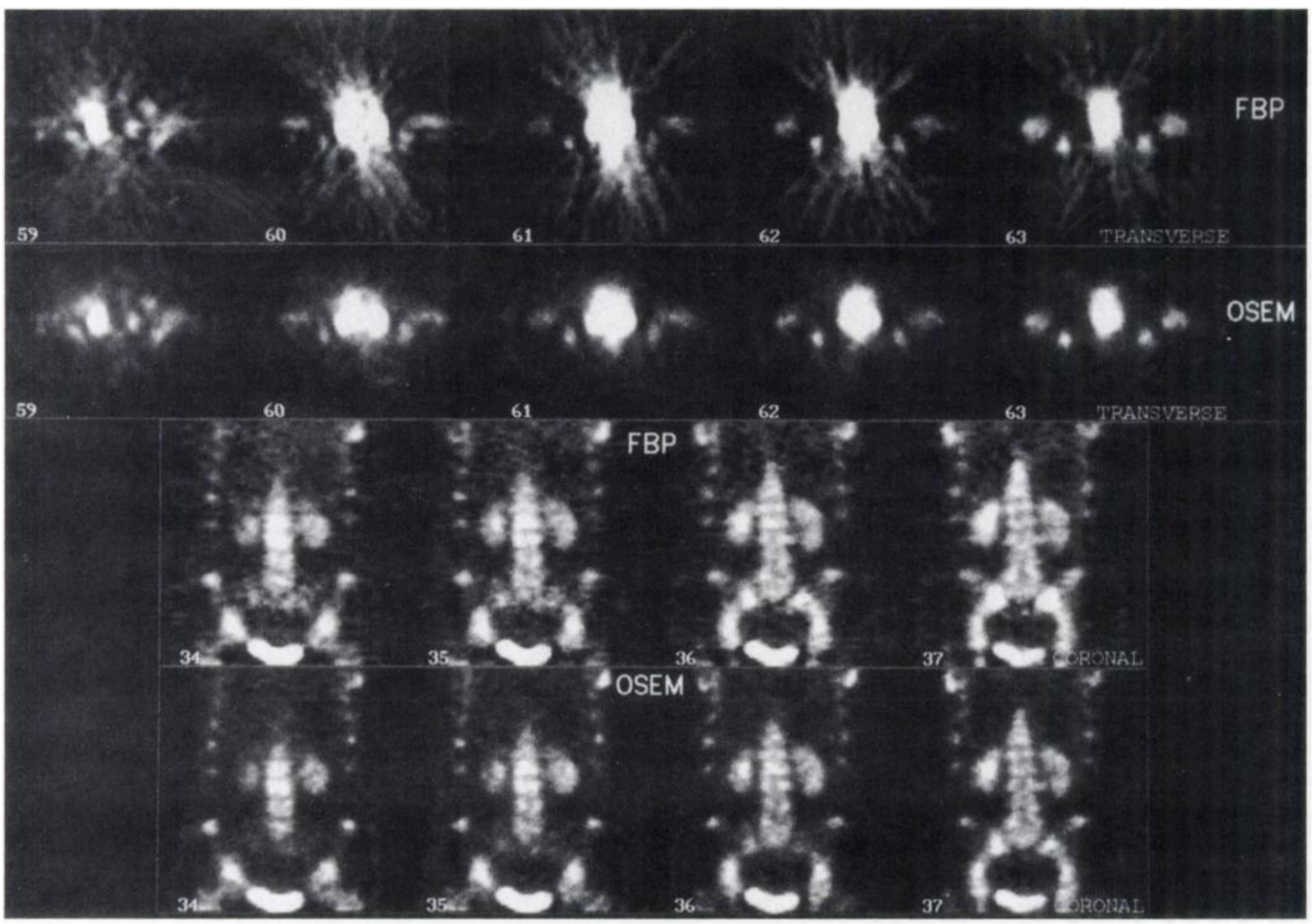

FIGURE 4. In some patients, hips were almost erased by filtered backprojection (FBP) technique, which generates negative values near high bladder activity. Ordered-subset expectation maximum (OSEM) method leads to interpretable pictures.

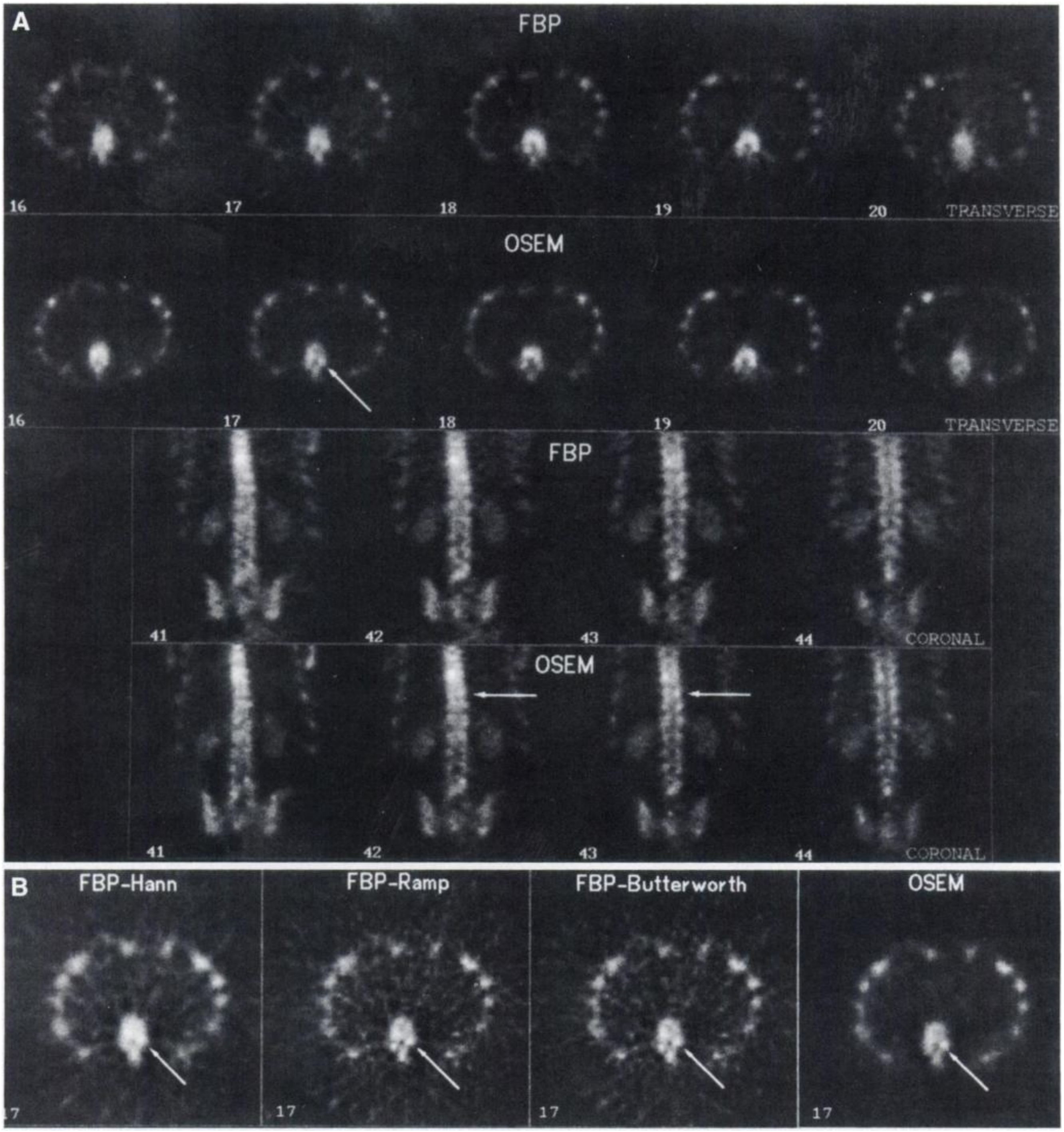

FIGURE 5. (A) Suspected borderline lesion was detected with only ordered-subset expectation maximum (OSEM) reconstruction method (arrow). Other lesions were also more precise with OSEM than with filtered backprojection (FBP). (B) Borderline lesion was visualized with FBP using less smoothing filter (ramp or Butterworth filter, order 10 and cutoff 0.5 cycle/pixel) than Hanning (Hann) filter (cutoff 0.5 cycle/pixel).

entirely controls the final resolution, contrast and noise of the reconstructed images (*15*). The limiting factor here is the noise. It first decreases with the iteration number. After a few tens of iterations in the MLEM and only a few iterations in the OSEM (with eight subsets), the noise starts to increase dramatically. A preliminary study of 10 cases (not included in this study) showed that two iterations gave visually the best compromise. Postfiltering of the reconstructed data or a noise regularization method based on priors could change the compromise toward more iterations, and therefore better contrast, but at the cost of a loss of resolution (*6,9,12,13*).

The FBP SPECT reconstruction method has some disadvantages. The most important disadvantages in spine SPECT are streak artifacts (Figs. 1–3) and negative values in the

TABLE 2
Number of Lesions

Reconstruction method	No. of observers	No. of lesions	%
Same number with both methods	3	48	84.2
More lesions seen with OSEM	3	1	1.8
More lesions seen with FBP	3	0	0.0
Same number with both methods	2	7	12.3
More lesions with OSEM	2	1	1.8
More lesions with FBP	2	0	0.0
Same number or one more lesion	3	57	100

OSEM = ordered-subset expectation maximum; FBP = filtered backprojection.

Total number of lesions = 57. Same number of lesions was generally observed with both reconstruction methods. In very few cases, one more borderline lesion was detected with OSEM.

TABLE 3
Definition

Parameter	No. of observers	No. of lesions	%
Anatomic definition			
Superior with OSEM	3	7	12.3
Identical with both techniques	3	7	12.3
Inferior with OSEM	3	0	0.0
Superior with OSEM	2	10	17.5
Identical with both techniques	2	31	54.4
Inferior with OSEM	2	0	0.0
Complete disagreement		2	3.5
Superior or equal to FBP	3	55	96.5
Lesion extent			
More precisely defined with OSEM	3	8	14.0
Identical with both techniques	3	8	14.0
Less precisely defined with OSEM	3	0	0.0
More precisely defined with OSEM	2	17	29.8
Identical with both techniques	2	22	38.6
Less precisely defined with OSEM	2	2	3.6
Identically or less extended with OSEM	3	55	96.5
Low-activity regions			
Better visualized with OSEM	3	13	22.8
Identical with both techniques	3	2	3.5
Better visualized with FBP	3	0	0
Better visualized with OSEM	2	19	33.3
Identical with both techniques	2	23	40.4
Better visualized with FBP	2	0	0.0
Better or identically visualized with OSEM	3	57	100.0

OSEM = ordered-subset expectation maximum; FBP = filtered backprojection.

Anatomic definition was found superior or equal to FBP pictures with OSEM method. In some cases, it was clearly superior. Lesions were identical or less extended in OSEM pictures. Low-activity regions were frequently better visualized after OSEM reconstruction.

border of highly active regions. In pelvic SPECT, negative values, sometimes almost erasing the hips (Figs. 2 and 4), are generated when significant bladder activity is present (*4,7,8*). The choice of a correct filter is not always easy. Moreover, any filtering operation leads to a global smoothing of the reconstructed volume. In particular, the hyperactivity becomes less focal because of spreading out of the activity on the nearby pixels (*1,2,5*).

In contrast, OSEM methods do not use any filter. This study shows that the OSEM is able to eliminate, at least partially, almost all artifacts observed with FBP. With FBP, 24 patients presented with significant negative artifacts near the bladder. Better results were obtained with the OSEM (Fig. 4), but this technique failed to satisfactorily eliminate the negative-value artifacts in 4 patients (Fig. 2). Measurement of bladder activity in the first and last projections of the SPECT study showed that the bladder contained high activity without further filling (<25%). In contrast, 6 patients with an evident filling (+103% to +227%) had interpretable OSEM pictures. The data presented in Figure 2, for which the counting statistics are poor because of the paravenous injection, remind us that the acquisition quality remains the key point of any scintigraphic investigation.

No lesion was missed with the OSEM, and few additional borderline lesions (Fig. 5A) were observed, indicating that no additional artifact occurred. However, using a less smoothing filter (ramp or Butterworth filter, order 10 and cutoff 0.5 cycle/pixel), the missed hyperactivity was retrieved in the FBP reconstruction (Fig. 5B). This case illustrates the theoretic necessity of selecting for all SPECT data the more appropriate filter when using FBP (*1,2*). The OSEM obviates any similar delicate testing.

The extent of the lesion was equally and sometimes better defined with the OSEM. A better visualization of the low-activity region was observed in many cases. These are known advantages of the OSEM (*16*).

When the observers commented on the global quality of

TABLE 4
General Impression

General impression	No. of observers	No. of lesions	%
Better with OSEM	3	37	64.9
Identical with both methods	3	1	1.8
Better with FBP	3	0	0.0
Better with OSEM	2	16	28.1
Identical with both methods	2	2	3.4
Better with FBP	2	0	0.0
Complete disagreement		1	1.8
Better or Identical	3	56	98.2

OSEM = ordered-subset expectation maximum; FBP = filtered backprojection.

General impression of reconstructed pictures was better after OSEM reconstruction in most cases.

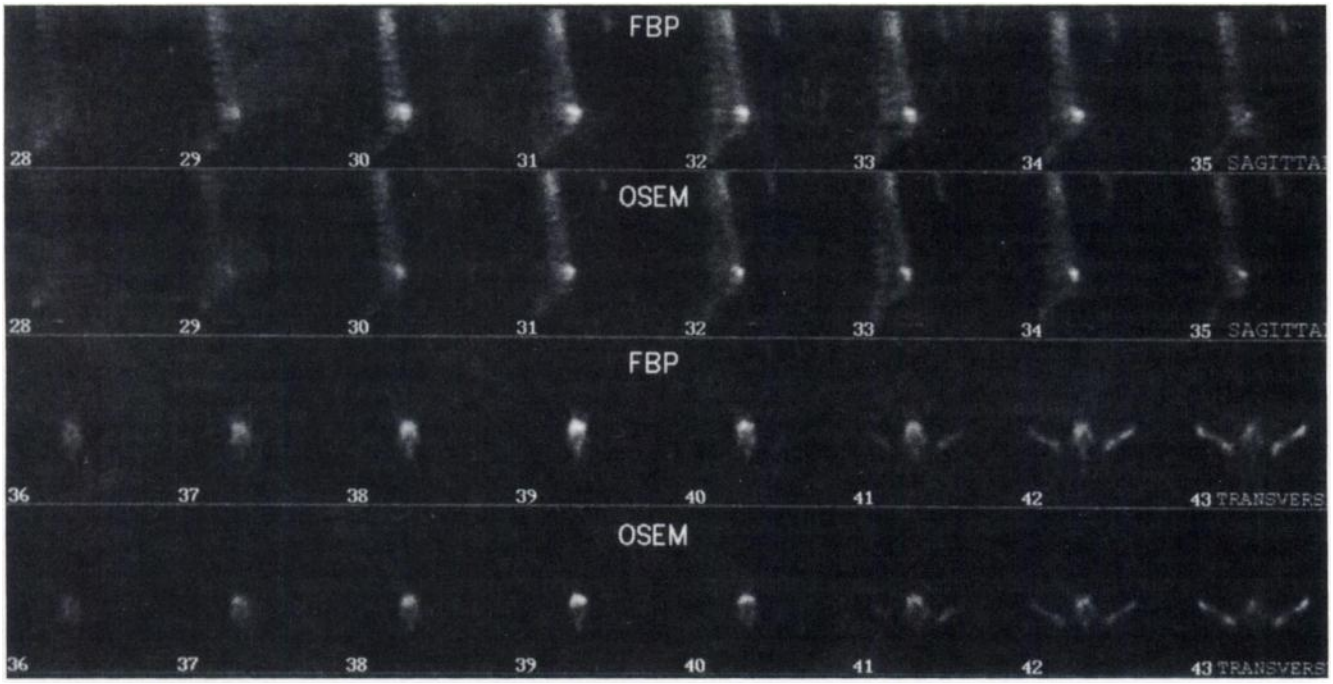

FIGURE 6. Lesions were more precisely defined with ordered-subset expectation maximum (OSEM) than with filtered backprojection (FBP).

the images, they considered those obtained with the OSEM to be superior in most cases (Table 4 and Figs. 1, 2 and 4).

CONCLUSION

The OSEM reconstruction method gives results at least equal and frequently superior to those of the classical FBP method in bone SPECT. Because the time (a few seconds) needed for reconstruction processing is relatively short for both methods with new-generation computers and improved algorithms, the OSEM could advantageously replace FBP for bone SPECT. Its application with other radiopharmaceuticals must be assessed. Some advantages for myocardial perfusion studies conducted with ^{99m}Tc-labeled radiopharmaceuticals have been reported, especially in the presence of extracardiac activity (*17*). For scintimammography using ^{99m}Tc-methoxyisobutyl isonitrile, recently published data clearly favor the MLEM and OSEM, with 10% of the FBP reconstructions being unreadable (*18*). This investigation confirms these figures. We have recently adopted the OSEM in ^{67}Ga SPECT, in which case the OSEM gives higher quality images than does FBP.

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