Bone and Liver SPECT

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This is the fourth and final article in a continuing education series on SPECT. After reading and studying this paper, the reader should be able to: 1) state the clinical indications for performing skeletal and liver SPECT studies; 2) discuss the data acquisition and processing of skeletal and liver SPECT; and 3) identify and correct technical pitfalls that occur when performing clinical SPECT procedures.

Recent survey data indicates that the bone scan is the most common in vivo nuclear medicine procedure in the United States (*1*). Given the high volume of bone scan examinations in most busy nuclear medicine laboratories, the commitment to total body imaging for oncology patients and the more recent trend toward flow study, blood pool, and delayed planar imaging—the "three-phase bone scan"—place substantial demands on the busy nuclear medicine department. Therefore, the suggestion that SPECT be added as an additional and at times fourth phase of the bone scan will be well received only if bone SPECT can be performed expeditiously with resultant tomographic images that provide unique diagnostic information.

Currently, SPECT of the skeletal system has been applied principally to the diagnostic evaluation of patients with pain and dysfunction in the larger joints and bony structures such as the knees, hips, lumbar spine, and temporomandibular joints (TMJ). The potential of SPECT skeletal imaging of radiopharmaceuticals other than [^{99m}Tc]medronate and the utility of the technique as a screening test in asymptomatic patients at risk for bone metastases has not been thoroughly investigated.

The potential diagnostic advantage of SPECT lies in examining bony structures for which there is substantial underlying or overlying activity which planar imaging techniques superimpose on the bony structures of interest. For example, in the hip the acetabulum extends downward behind the femoral head. Therefore, the photon deficient defect typical of avascular necrosis (AVN) of the femoral head may be obscured on anterior view planar images by activity originating in the underlying acetabulum. However, it is possible to separate underlying and overlying distributions of activity into sequential tomographic images by using SPECT. For this reason, SPECT facilitates the detection of femoral head AVN (*2*).

IMAGING CONSIDERATIONS

SPECT complements but does not replace information available with planar bone imaging, and therefore the time and expense for SPECT is an addition to the total cost of the bone scan. Furthermore, many patients complaining of skeletal pain and dysfunction may also benefit from flow study and blood-pool images. Consequently, SPECT is often the fourth imaging phase of a patient's bone scan. In our laboratory, the imaging sequence for patients without known malignancy complaining of significant knee, hip, low back, or TMJ pain is as follows:

1. Flow study (5 sec/frame).
2. Blood-pool image (500,000 counts).
3. Planar images.
4. SPECT.

Because for some adult patients the diagnostic quality of SPECT may be count limited, the adult dose of 25 mCi of [^{99m}Tc]medronate is used.

Positioning for Bone SPECT

Bone SPECT positioning requires that the patient lie supine and immobile on the imaging table for over 21 min of data acquisition. Patients suffering from musculoskeletal pain often find it difficult to remain immobile, and any measures which will increase patient comfort and motivation are warranted.

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For example, securing legs and arms with straps will increase patient comfort, and an additional pillow under the head or knees often will help. Finally, the importance of bilateral symmetric skeletal positioning for an optimal bone SPECT examination should be emphasized. Bilateral symmetric positioning of bony structures (e.g., having both knees equally extended and in a neutral position) results in SPECT images for which any left-to-right asymmetry is caused by skeletal pathology rather than variations in positioning. Special considerations when positioning patients for the most common bone SPECT examinations are listed in Table 1.

Data Acquisition

Data acquisition should be performed only with a rotating scintillation camera that has successfully passed previously described quality control tests (*3*). Whereas high resolution collimators, slant hole collimators (*4*), or special purpose head collimators (*5*) may be used, the low-energy general purpose collimator provides a trade-off between resolution and sensitivity which is usually acceptable for bone SPECT. Furthermore, for a circular 400-mm field-of-view camera, we have found that bone SPECT data acquired by our standard protocol (64×64 matrix, 64 projections over 360° of circular rotation, 20 sec/projection) does not suffer from loss of resolution or incomplete angular sampling artifacts.

Data Processing of Bone SPECT

Data processing begins by first performing a uniformity correction and then a 9-point spatial smooth on each of the 64 projections. Following this preprocessing of the 64 projections, one-slice thick transaxial, coronal, and sagittal tomograms ($\sim$ 6-mm thick) are reconstructed using filtered backprojection with a ramp Hanning filter (cut-off frequency of 10 cycles/pixels or greater). Attenuation correction is not used. For most bone SPECT studies, a linear map is used when photographing SPECT images onto transparencies. However, in searching for a photopenic defect in the femoral head at risk for AVN, the log map is usually preferred.

Review and Interpretation of Bone SPECT

Bone SPECT review and interpretation by physicians requires that all bone scan images be available simultaneously. Our experience indicates that both planar images and all three orthogonal sets of SPECT images are often needed when attempting to identify and localize skeletal abnormalities. For a short time after the SPECT technique is adopted by a laboratory, physicians seeking to assure themselves that optimal image enhancement has been used will need to review SPECT images at the computer terminal. However, when technologists become adept at optimally photographing bone SPECT images onto transparencies, no more than 10% of bone SPECT cases will require such review.

CLINICAL APPLICATIONS

Many bony structures suitable for SPECT imaging have not been studied in detail, and the potential of bone SPECT for oncologic imaging has not been thoroughly investigated. However, current clinical experience has shown a role for bone SPECT in examining patients for whom there is clinical suspicion of certain specific morbid conditions involving the knees, hips, lumbar spine, or TMJ.

Knees

Twenty-seven patients with chronic knee pain were prospectively examined by conventional radiography and bone scanning with SPECT (*6–8*). When the results of subsequent arthroscopic examination of all three compartments of the knee were reviewed, bone SPECT was found to be the most sensitive noninvasive test for evaluating the extent of osteoarthritis. Differences in detection sensitivity for articular cartilage damage and synovitis were greatest in the patellofemoral compartment where the 0.91 sensitivity of bone SPECT compared favorably with the results of planar bone imaging, conventional radiography, and clinical examination. Furthermore, both SPECT (1.00) and planar (0.91) bone scanning were highly sensitive indicators of chronic meniscus tears in a subgroup of 14 patients with the pre-arthroscopic clinical diagnosis of a torn meniscus. Results suggest that bone scanning, particularly when augmented with SPECT, has potential as a high sensitivity screening examination in patients with osteoarthritis or other significant internal derangement of the knee.

TABLE 1. Special Patient Positioning for Bone SPECT

Bony Structure	Special Positioning	Pitfalls
Knees	2″–3″ pad between knees. Secure knees with straps to prevent motion. Secure feet in neutral position to prevent rotation.	For obese patients both knees may not fit in field-of-view.
Hips and Pelvis	Empty bladder before exam. Position hips symmetrically and secure knees and/or feet to prevent motion.	Bladder filling during exam creates artifacts.
Lumbar Spine	Keep arms out of field-of-view. A pillow under the knees may relieve back pain.	Patients with back pain often move during the exam.
TMJ	Secure neck in comfortable hyperextension. Instruct patient not to talk.	Check lateral view to be sure the chin is in the field-of-view.

Hips

Twenty-one patients with the clinical diagnosis of AVN of the femoral head were examined by conventional radiography and bone scanning with SPECT (*2*). A final diagnosis of AVN was established for 15 symptomatic patients with a total of 20 involved hips. SPECT and planar bone scintigraphy were considered positive for AVN only if a photopenic bony defect could be identified. Using bone SPECT, 17 of 20 hips (sensi-

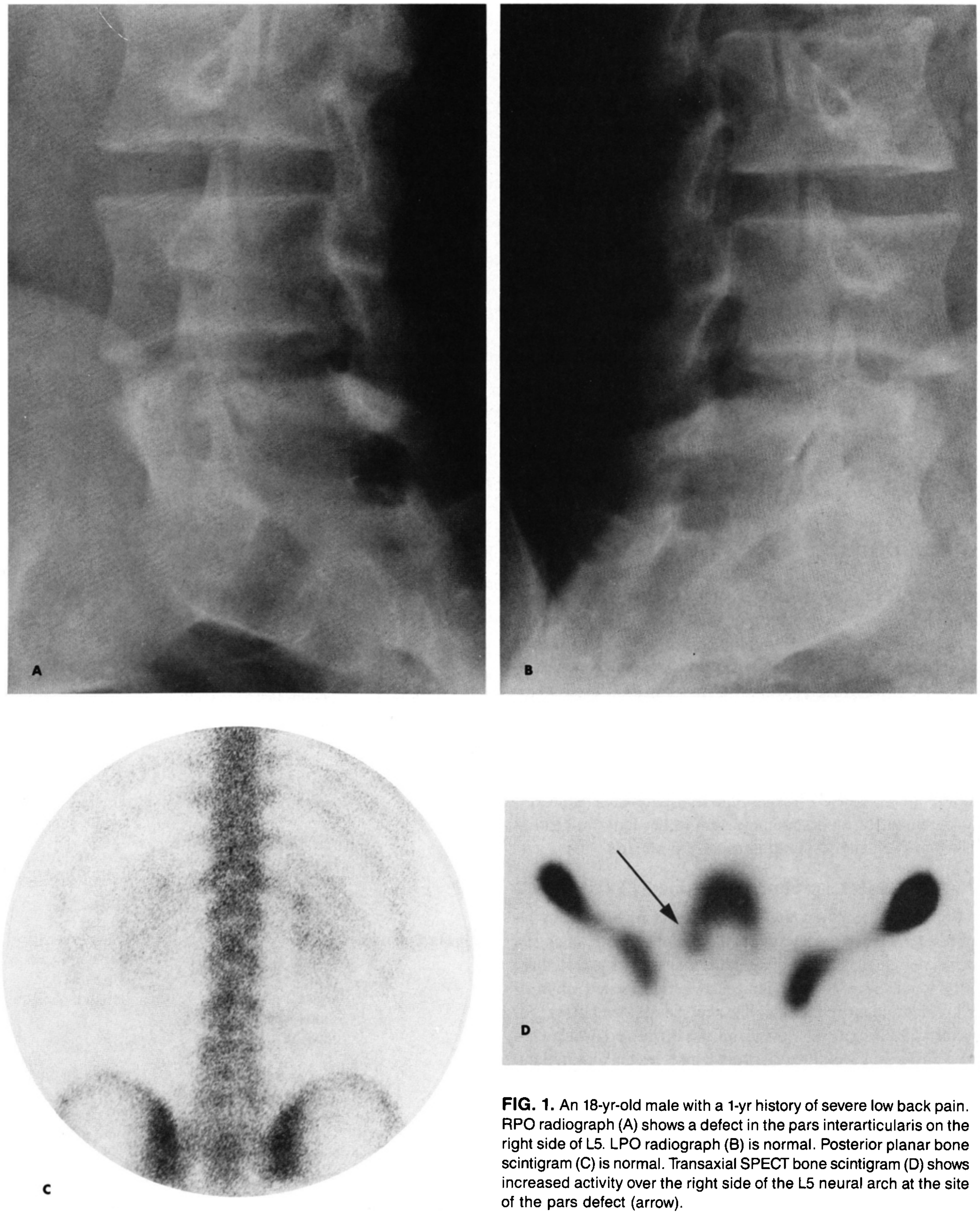


FIG. 1. An 18-yr-old male with a 1-yr history of severe low back pain. RPO radiograph (A) shows a defect in the pars interarticularis on the right side of L5. LPO radiograph (B) is normal. Posterior planar bone scintigram (C) is normal. Transaxial SPECT bone scintigram (D) shows increased activity over the right side of the L5 neural arch at the site of the pars defect (arrow).

tivity of 0.85) were correctly identified whereas with planar imaging only 8 of 15 patients and 11 of 20 involved hips were detected. Whereas 13 of 20 hips with AVN had radiographic abnormalities at the time of the initial bone scan, a subchondral fracture—the most specific radiographic finding of early femoral head AVN—was present in only six instances. In identifying a photopenic defect that is not evident on planar views, SPECT can contribute to the accurate diagnosis of AVN of the femoral head.

Lumbar Spine

Planar and SPECT bone scanning were compared in 19 adults with radiographic evidence of spondylolysis and/or spondylolisthesis of the lumbar spine (*9*). SPECT was more sensitive than planar imaging when used to identify symptomatic patients and sites of "painful" defects in the pars interarticularis (Fig. 1). Furthermore, SPECT allowed more accurate localization of abnormalities in the posterior neural arch. When spondylolysis or spondylolisthesis is the cause of low back pain, pars interarticularis defects are frequently associated with increased scintigraphic activity that is best detected and localized by SPECT.

Temporomandibular Joints

The diagnostic accuracy of conventional radiography, arthrography, and both SPECT and planar bone scanning were

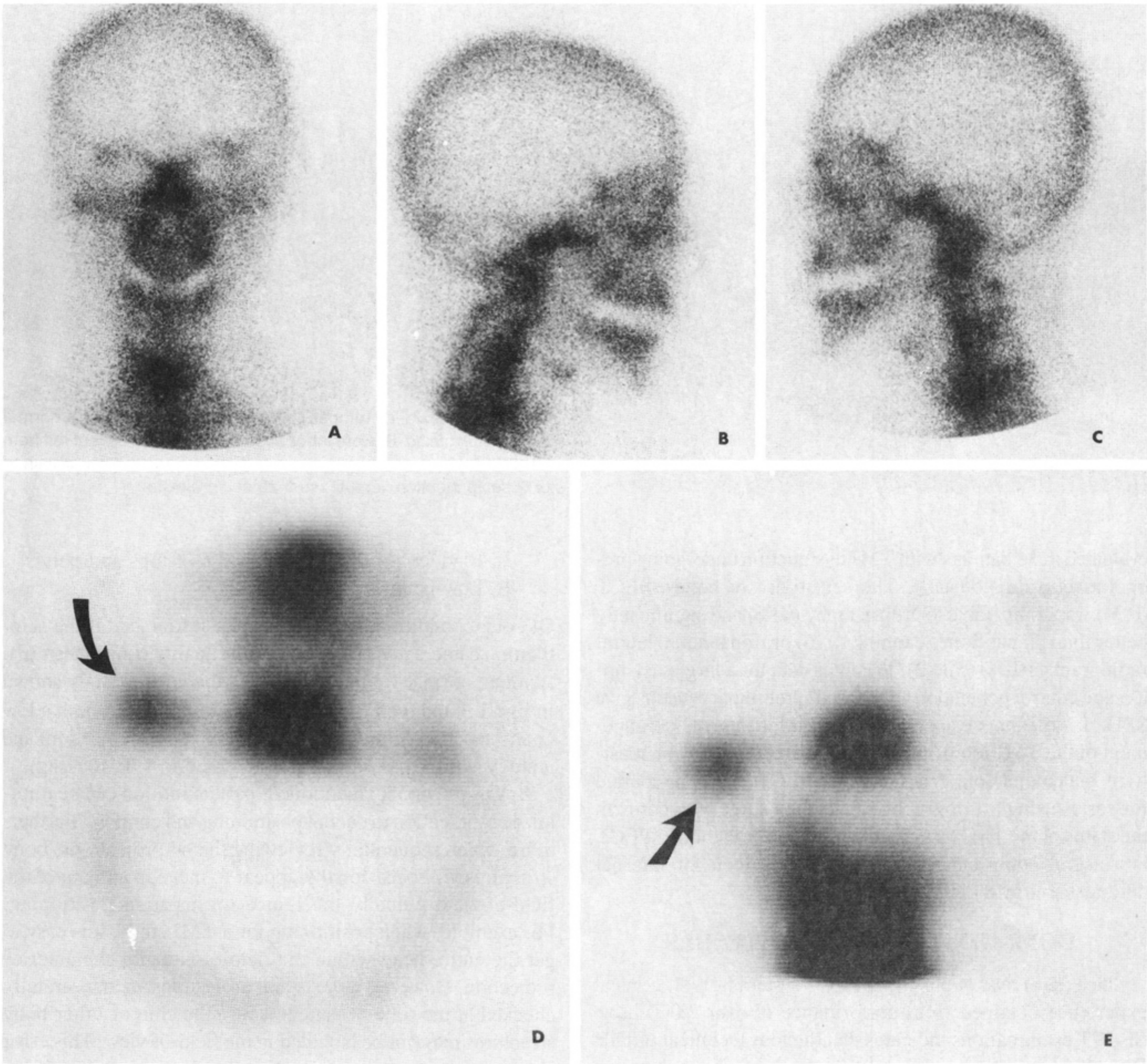
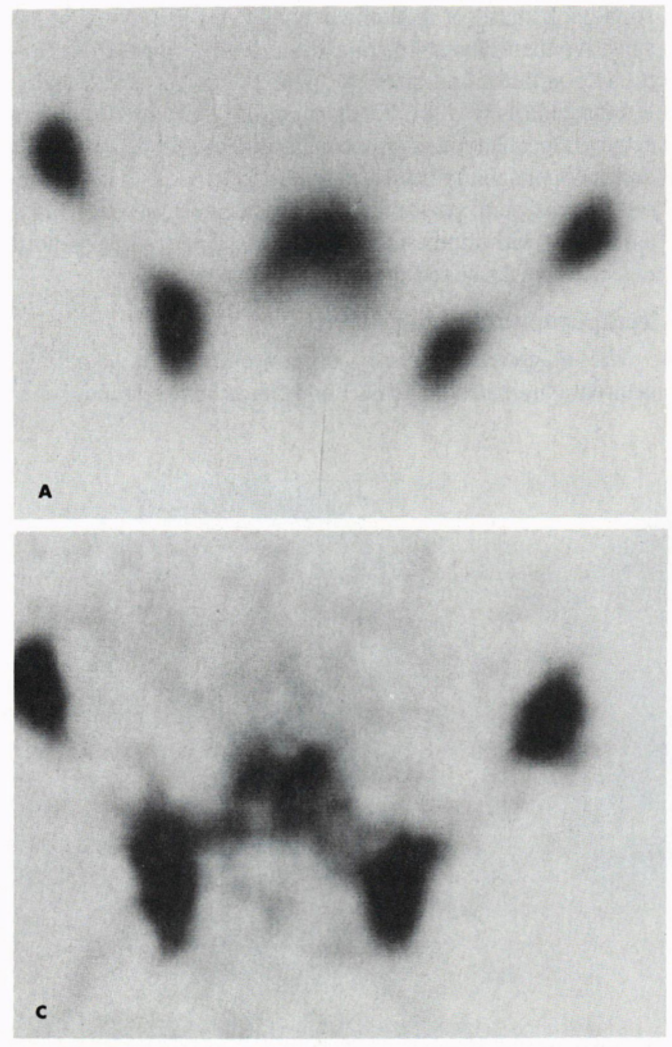


FIG. 2. A 43-yr-old female had severe right sided facial pain and limited opening of the jaw. Anterior (A). right lateral (B), and left lateral (C) planar bone scintigrams show prominent activity about both TMJs. Transaxial (D) and coronal (E) SPECT images show increased activity about the right TMJ (arrows) with the left TMJ normal.



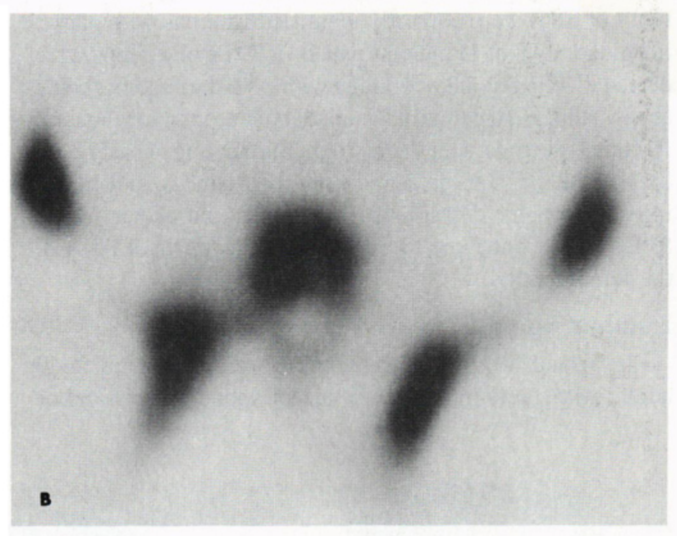


FIG. 3. Transaxial L5 lumbar spine SPECT image (A) for a normal volunteer. Artifacts (B) were introduced by having the patient roll from side to side during data acquisition. Low count study (C) was obtained for 2 sec/projection versus usual 20 sec/projection.

evaluated in 36 patients with TMJ dysfunction undergoing preoperative evaluation (*10*). The sensitivity of bone SPECT (0.94) was comparable to arthrography (0.96) and significantly better than planar bone scanning (0.76) or transcranial lateral radiography (0.04) (Fig. 2). Whereas data for a larger asymptomatic control population are needed, preliminary results give SPECT a diagnostic specificity of 0.70 for internal derangement of the TMJ requiring surgical correction. Lower sensitivity but comparable specificity for SPECT has been reported for series using arthrography rather than surgery to confirm the status of the TMJ (*11,12*). It is concluded that bone SPECT is a useful noninvasive imaging test to screen for internal derangement of the TMJ.

COMMON TECHNICAL PITFALLS

Since the arrival of our first SPECT system in 1981, clinical experience obtained from performance of over 2,000 bone SPECT examinations indicates that the four technical pitfalls listed below (in order of decreasing frequency) are the most commonly encountered problems:

1. Patient motion.
2. Bony structure moving in and out of the field-of-view.
3. Bladder filling during SPECT of hips and pelvis.
4. Low count study.

Of course, additional artifacts can be introduced if the scintillation camera does not pass routine quality control tests (*3*). A young normal volunteer provided the normal study shown in figure 3 and then cooperated for simulations of both a low count study (2 sec/projection instead of 20 sec/projection) and a study with gross patient motion (side-to-side rocking).

As was previously mentioned, patient motion can be minimized by attention to patient positioning and comfort. Furthermore, when sequentially reviewing the 64 projections, bony structures will occasionally appear to move in and out of the field-of-view. Actually, this is an error in patient positioning. For example, when positioning for a TMJ study, it is easy to get the entire head within the field-of-view for the anterior projection. However, if the lateral projections are not carefully checked at the time of patient setup, the chin or other bony structures may not be included in the field-of-view. This error in positioning creates incomplete angular sampling artifacts that may compromise the diagnostic quality of the examination.

Data should be routinely reviewed before the patient leaves the department, and occasionally it will be necessary to re-

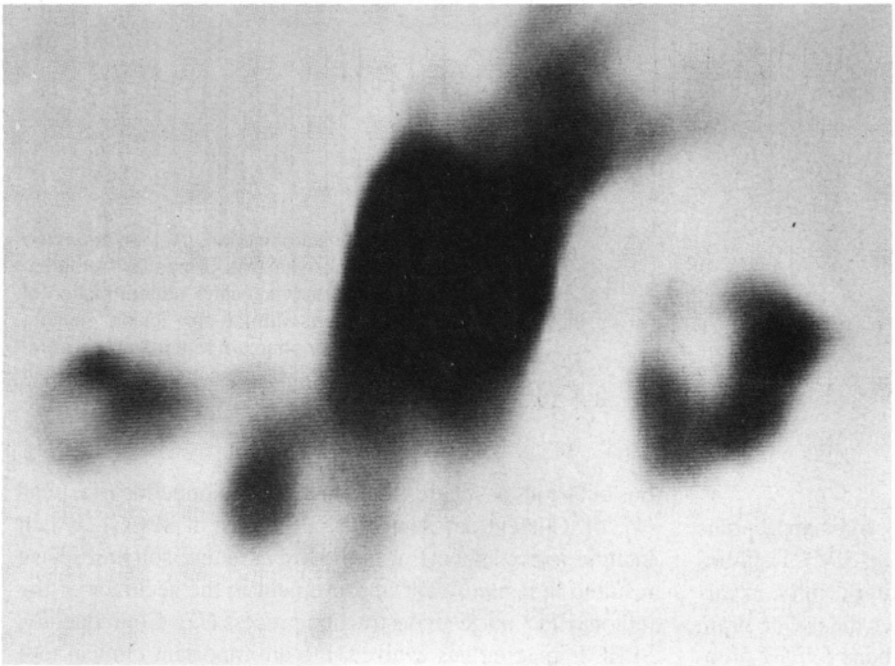


FIG. 4. Transaxial SPECT image through the femoral heads that was obtained when the patient's bladder filled rapidly during the time of data acquisition. Broad rays projecting beyond the bladder obscure the femoral heads.

acquire a SPECT study because of gross patient motion. Low count studies may occur because of limited camera facilities or unexpected emergency studies which extend a bone SPECT study well after the recommended 3-hr period between injection and imaging. Extending the time per projection to 30 or 40 sec will correct for this problem.

Although patients are asked to void before SPECT data acquisition, rapid bladder filling still contributes to unsatisfactory examinations of the hips and pelvis in approximately 20% of patients. Figure 4 shows a bone SPECT image which is rendered unacceptable by rapid bladder filling during the time of data acquisition. As the 64 sequential projections were acquired, activity within the bladder increased. On the transaxial image, broad rays project beyond the bladder and in part

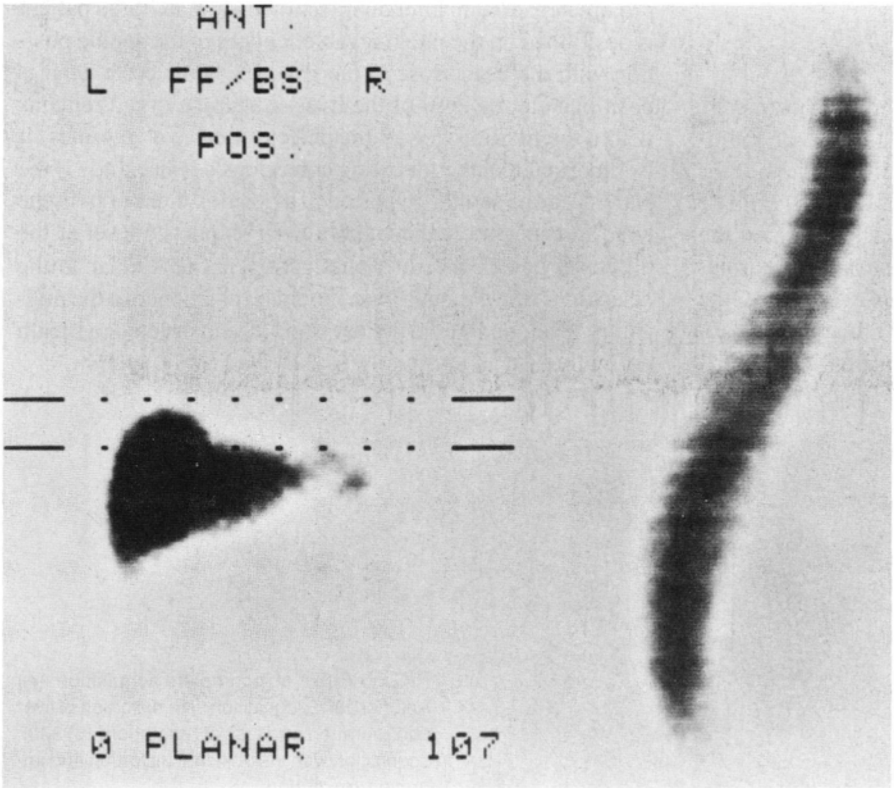


FIG. 5. Position of 6-pixel width horizontal profile (left) used to generate normal patient sinogram (right) from 128 acquired projections.

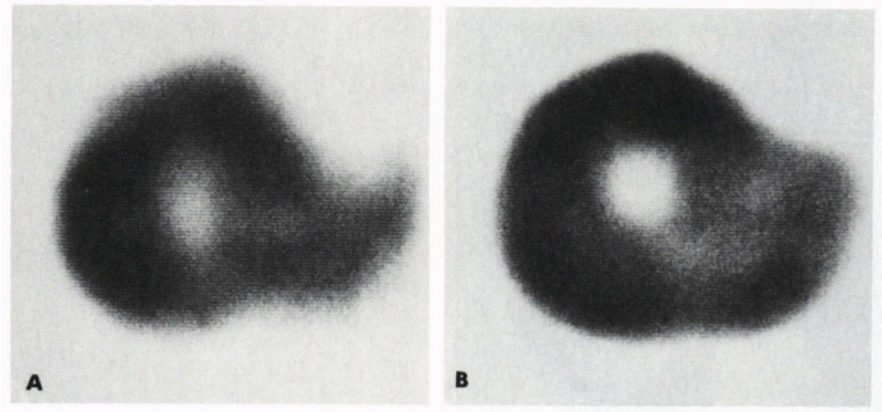


FIG. 6. Effect of motion. (A) Marked image degradation with loss of spatial resolution from simulated excessive patient motion of liver phantom with 2.8 cm "lesion" in right lobe. (B) Liver phantom without motion demonstrates good delineation of right and left lobes.

obscure the femoral heads.

Artifacts caused by camera nonuniformity and inappropriate center of rotation have not occurred in bone SPECT studies performed at our institution. Whereas nonuniformity, in particular, may be more troublesome for liver, heart, or brain SPECT, the high image contrast inherent to bone SPECT probably accounts for the extreme rarity of this artifact in our series.

The addition of SPECT to each routine bone scan requires an extra 5 min for setup and patient positioning, 21 min for data acquisition, and 15 min for processing and filming. For patients with knee, hip, low back, and TMJ pain, bone SPECT frequently gives images of greater clarity and, in many instances, provides unique diagnostic information. Specific advantages of SPECT in identifying and localizing skeletal pathology already have been established, and further diagnostic applications for skeletal oncology and the study of low back pain are anticipated.

LIVER SPECT

Since the introduction of colloid radiopharmaceuticals, specifically ^{99m}Tc-sulfur colloid in 1964, the planar radionuclide liver scan has been an important diagnostic tool for the evaluation of both focal and diffuse liver disease (*13*). For many years, the radionuclide liver scan was considered the most important diagnostic modality in the noninvasive evaluation of space occupying liver disease (*14*). Recently, the increased availability and utilization of other imaging modalities, particularly ultrasound and CT scanning, has raised serious questions as regards the role of the radionuclide liver scan (*15,16*). Current developments in the area of SPECT, which include improvements in both hardware and software, have resulted in a significant improvement in the accuracy of the radionuclide image reconstruction process (*17*). Consequently, SPECT imaging has evolved into an important clinical tool for the evaluation of liver disease. In order to fully appreciate this methodology, it is important that the technical and theoretical aspects of the procedure be well understood.

For the purpose of discussion, SPECT imaging can be divided into the following segments: 1) acquisition; 2) processing; 3) quality control; and 4) interpretation.

ACQUISITION

Technetium-99m sulfur colloid currently remains the radiopharmaceutical of choice for hepatic SPECT imaging. Approximately 20 min after an injection of 4–5 mCi, the patient is positioned on the imaging table (couch) in the supine position with the head close to the gantry. The detector head is positioned at the level of the liver so that the organ remains within the field-of-view of the detector device at all times. It is important that the following conditions be observed: 1) the patient's arms should be placed in a position clear of both the liver and spleen; 2) the camera head should be level at the 0° position with the rotational gantry perpendicular to the detector; 3) the patient's liver should be positioned at the midgantry level; and 4) the patient should be instructed to breath normally.

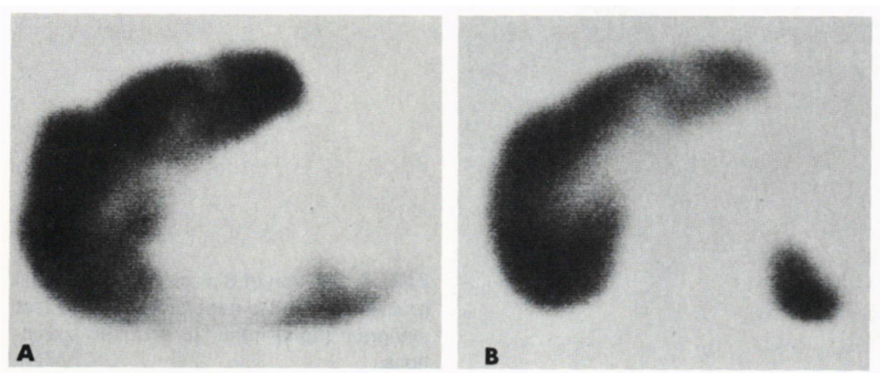


FIG. 7. Effect of incomplete acquisition. (A) Anterior 180° acquisition with distortion of liver configuration and loss of resolution. (B) 360° acquisition with insignificant distortion and improved resolution.

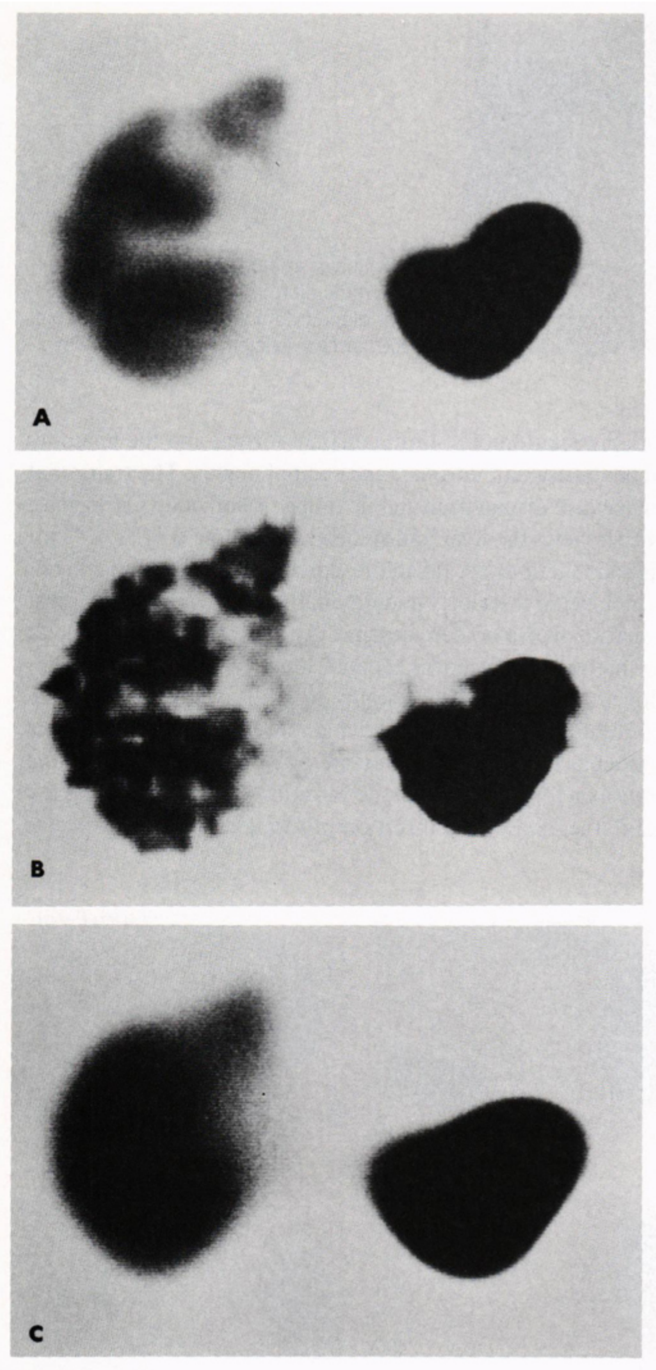


FIG. 8. Effects of filtration. (A) Underfiltered (excessive noise) image. (B) Properly filtered image with good delineation of porta hepatis. (C) Overfiltered (excessive smooth) image.

Although most commercial systems currently use a circular rotation orbit, it is anticipated that either elliptical orbits or possibly body contour orbits will be available in the near future. These modifications in the rotation orbit should result in improved spatial resolution and greater image contrast because the source is closer to the imaging device (*18*). In addition, most current single-photon imaging devices operate in a step and shoot acquisition mode. During this mode, the camera head moves a predefined increment to a set location and an image is acquired for a predefined period of time. An alternative is for the system to operate in a continuous acquisition mode with or without continuous rotation. Controversy still exists as to which of these methods will ultimately prove to be best in a clinical environment.

Image data are acquired in a 64 × 64 matrix format. A total of 128 views (10 sec/view) are obtained over a full 360° of rotation. The total acquisition time is 23 min. Images are uniformity corrected on the fly and subsequently displayed in a closed-loop cine format. The cinematic display is used as a quality control procedure along with a horizontal profile (sinogram) display (Fig. 5) for the evaluation of: 1) patient position; 2) excessive patient motion; 3) dropped frames; and 4) detector sag. In addition, the cinematic display supplies useful information of a three-dimensional nature.

IMAGE PROCESSING

There are a number of different algorithms for the image reconstruction process. Our technique consists of attenuation correction of the projection images and subsequent image reconstruction using a Ramp (cutoff frequency 0.5 × the sampling frequency) filter. The resultant cross sectional images then undergo post-processing with both linear and nonlinear three-dimensional filters. Other approaches involve preprocessing the planar images using two-dimensional spatial filters prior to the reconstruction.

Irregardless of the approach used, it is essential that the methodology be validated experimentally with computer simulations and organ phantom studies as well as clinically through documentation and comparison of the examination results with other imaging procedures, clinical course, and final diagnosis. Inappropriate filtering techniques can result in inaccurate image reconstructions. Figures 6, 7, and 8 demonstrate degradation of spatial resolution caused by excessive patient motion, incomplete acquisition, and improper filtering, respectively.

The hepatic SPECT data are routinely reconstructed, displayed, and interpreted in the transaxial, coronal, and sagittal projections with a slice thickness of 1–2 pixels (6–12 mm). Oblique angle projections are used only as an adjunctive technique for evaluation of questionable ductal and/or vascular structures.

QUALITY CONTROL

The success of the entire imaging procedure is dependent on performing the study under optimum imaging conditions. To assess and ensure that the examination was properly obtained, it is essential that a number of quality control procedures be carried out on a routine basis. Greer, et al. (*19*), have described in detail the importance of quality control and the frequency at which the various procedures should be performed. In addition to the assessment of the acquired patient data using sinograms and cinematic displays, it is important to evaluate and correct camera field uniformity problems. To avoid nonuniformity artifacts, the acquired planar images are uniformity corrected using data which has been obtained (30

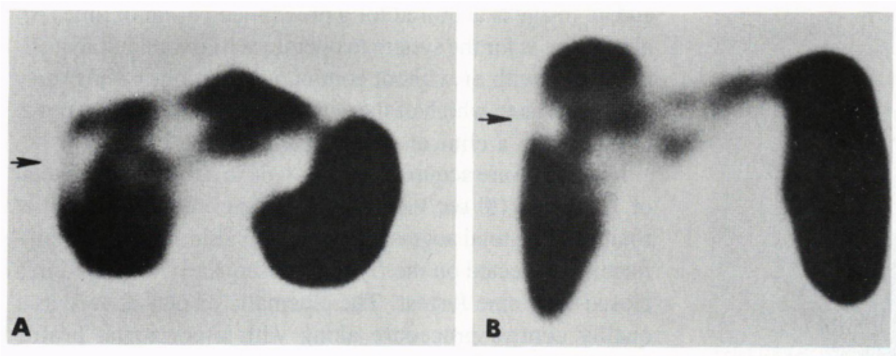


FIG. 9. Image artifact caused by focal camera field nonuniformity. (A) Transaxial and (B) coronal planes demonstrate resultant focal "defect" (arrows) in lateral aspect of right lobe.

million count) from a ^{99m}Tc flood phantom on the same day as the patient examination. As illustrated in figure 9, inadequate uniformity correction can result in an image artifact (*20*). In addition, center of rotation determinations are performed at our institution on a daily basis. A significant deviation (> 0.5 pixels) of the center of rotation can result in image artifacts (*21*). Both of these image artifacts could be misinterpreted as abnormal findings if the physician responsible for reporting the study was unaware of the technical problem.

INTERPRETATION

Accurate interpretation of hepatic SPECT images requires an appreciation of both the display format and the anatomy in the transaxial, coronal, and sagittal planes. The transaxial images are displayed in classic transmission body CT format, which views the liver and spleen from below (Fig. 10). Contiguous sections are taken through both the liver and spleen, which begin inferiorly and gradually progress up to the most superior aspect of these organs. The area that is most difficult to interpret is the porta hepatis. Identifying the wide variation in normal portal anatomy as well as variations in the configuration of the caudate and quadrate lobes (Fig. 11) is particularly important. Other areas of potential pitfalls on the transaxial projections include variations in anatomy of the left lobe, the area of the insertion of the falciform ligament, as

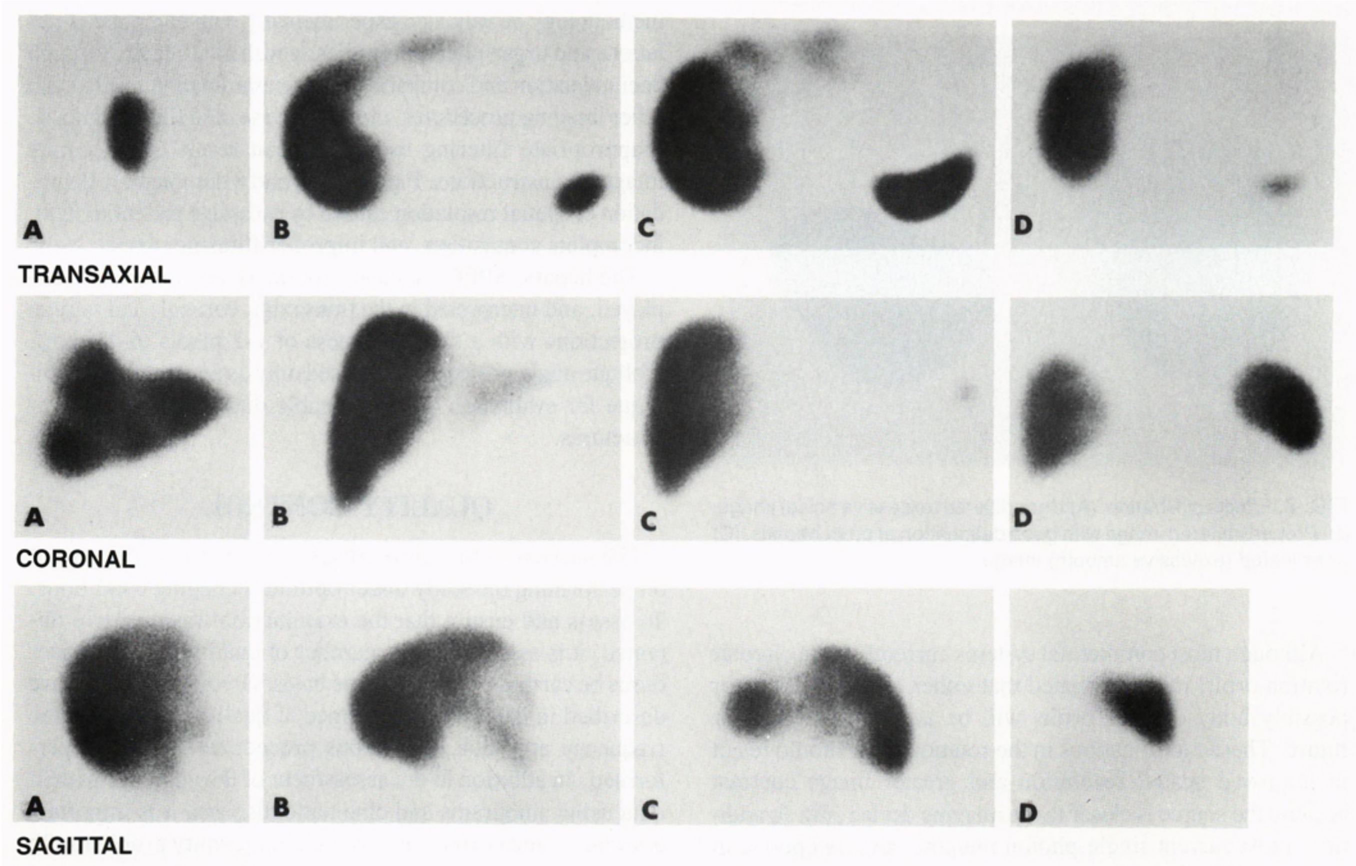


FIG. 10. Normal hepatic SPECT study. Transaxial plane (upper row). Coronal plane (middle row). Sagittal plane (lower row).

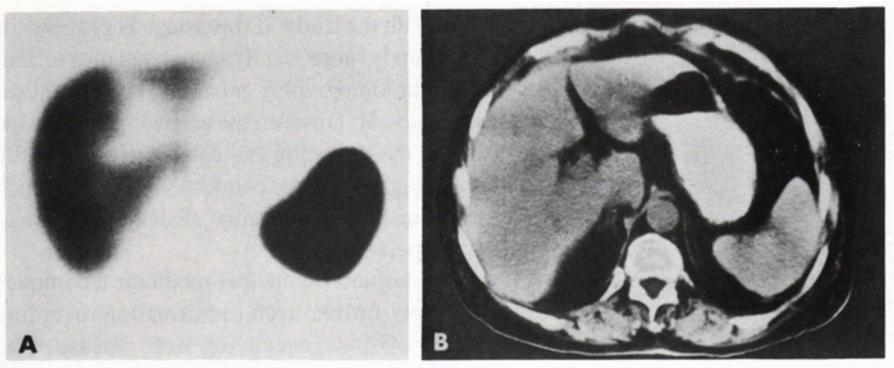


FIG. 11. Normal porta hepatis anatomy. (A) Transaxial SPECT image. (B) Comparable CT image. Both images demonstrate normal porta hepatis with right, left, quadrate, and caudate lobes well visualized.

well as the gallbladder and renal fossae.

Coronal sections are displayed in the same format as an anterior planar view of the liver and spleen (Fig. 10). The image reconstructions begin anteriorly with visualization of the left lobe. Contiguous slices continue through the porta hepatis and the entire right lobe. In addition to the pitfalls described above, other areas of potential difficulties caused by normal anatomic variation include the site of hepatic vein insertion as well as extrinsic pressure defects from costal impressions and body habitus.

The sagittal reconstructions, however, are projected in the same fashion as the right lateral planar images of the liver (Fig. 10). The image sections begin on the right side of the patient's body. Contiguous sections pass through the right lobe, porta hepatis, and left lobe of the liver. In the presence of disease, it is essential that the individual interpreting the exam have a strong understanding of cross-sectional anatomy of the abdomen, and the pathophysiology of the specific disease process being evaluated.

Presently, hepatic SPECT imaging has been found to be

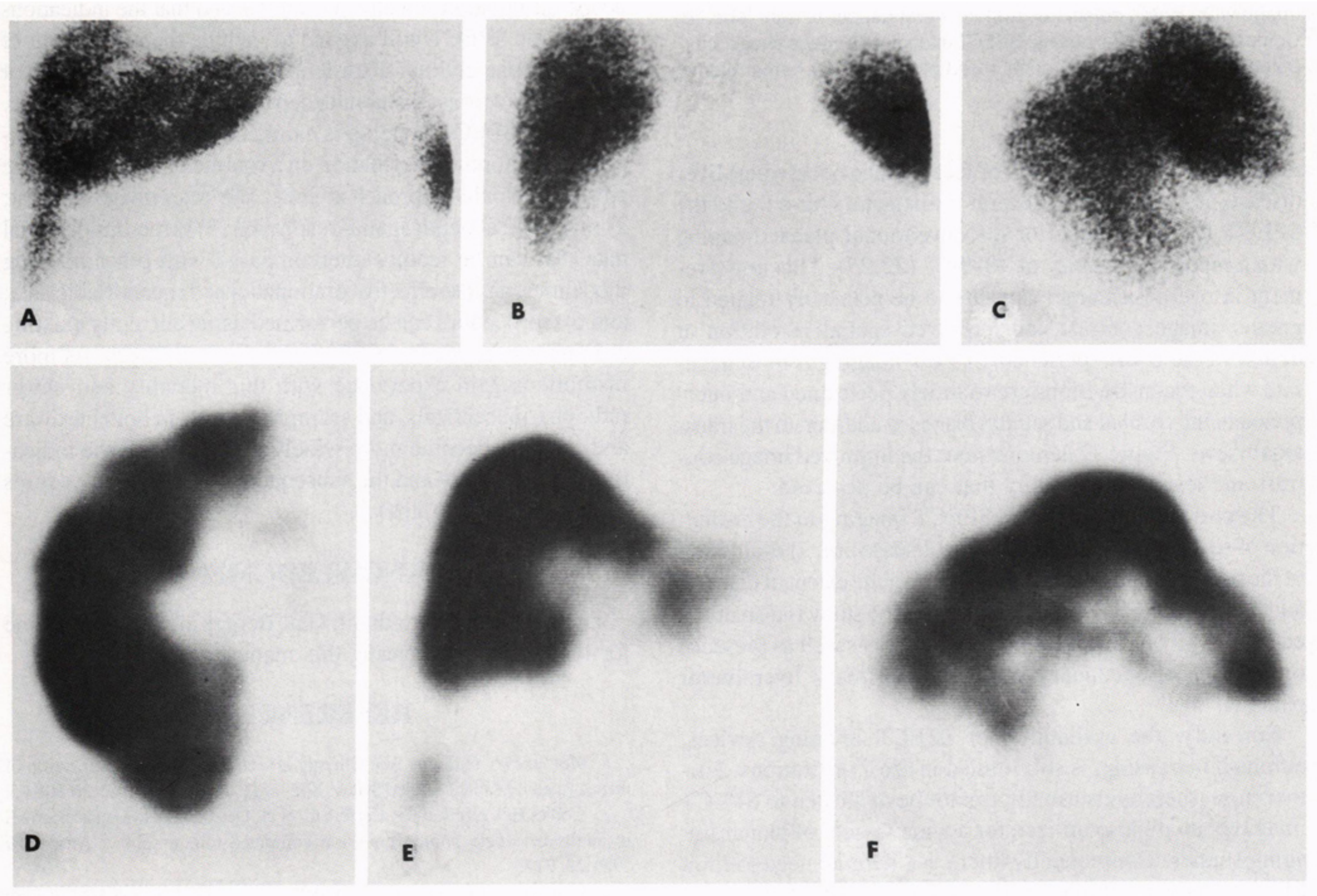


FIG. 12. Primary hepatocellular carcinoma of common hepatic duct with extension into right hepatic duct. Planar views (upper row) are negative for focal disease. Transaxial, coronal, and sagittal sections (lower row) reveal photopenic defect (carcinoma) in porta with more proximal defects caused by dilated ducts.

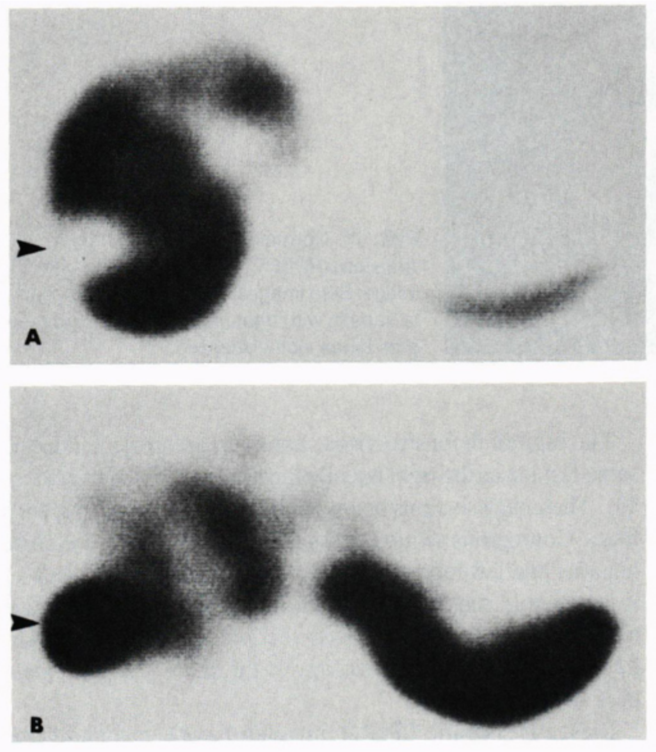


FIG. 13. Hepatic hemangioma. (A) Transaxial hepatic SPECT (colloid) image with "cold" defect (arrows) in lateral aspect of right lobe. (B) Comparable transaxial hepatic SPECT (blood pool) image shows "hot" defect caused by sequestration of red blood cells by hemangioma.

most useful in the evaluation of focal (space occupying) liver disease. In this instance, several investigators have found the SPECT technique superior to conventional planar imaging with a reported accuracy of 90–94% (*22,23*). This improvement in overall accuracy appears to be primarily related to greater image contrast and improved spatial resolution at depth. In our own experience, SPECT imaging is most accurate when reconstructions are routinely performed and interpreted in the coronal and sagittal planes in addition to the transaxial views. Figure 12 demonstrates the improved image contrast and lesion detectability that can be achieved.

The current uses of hepatic SPECT imaging in the evaluation of suspect or known metastatic disease are: 1) evaluation of the presence of disease; 2) evaluation of the extent of disease; and 3) followup of documented disease. The study is also utilized specifically to assess lesion resectability as well as presence or absence of secondary deposits in primary liver tumor patients.

Currently, the availability of SPECT imaging devices, although increasing, is still limited in most institutions. Furthermore, these units usually cannot be dedicated to SPECT imaging but are also utilized for a wide variety of planar imaging studies. Consequently, there is a definite need to limit SPECT studies to those patients who would benefit the most from this additional information. Our own approach is to first obtain an anterior planar image of the liver in patients suspected of focal liver disease. This image is analyzed by the physician involved with the study. If this image is positive for focal disease, the exam is subsequently completed on a scintillation camera without tomographic capability using conventional planar techniques. If, however, the anterior planar image is felt to be negative, the technologist then performs a SPECT study without obtaining any further conventional images. Such an approach ensures maximum utilization of all available imaging equipment and personnel.

In some instances, adjunctive nuclear medicine techniques are indicated to supply further useful information regarding the characterization of space occupying liver disease. One particularly helpful approach is the performance of a hepatic blood-pool study using SPECT technique to assess for the presence or absence of hepatic hemangiomata (*24*). Figure 13 demonstrates how much easier it becomes to evaluate and intercompare focal hepatic lesions on corresponding cross-sectional slices from multiple imaging modalities such as ultrasound, CT as well as radiocolloid and blood-pool hepatic SPECT images. Such an approach gives additional insight as to the location, extent, and physical characteristics of the lesion which would not be obtainable from a single study. In the future, other types of radionuclide imaging procedures including gallium and radiolabeled monoclonal antibodies will also be employed in an analogous fashion to supply further diagnostic information. Finally, it is anticipated that the indications for hepatic SPECT will expand to include the assessment of various hepatocellular disorders, trauma, and quantitation of such parameters as functioning hepatic volume and tumor size.

Hepatic SPECT imaging is a modality that can supply important additional information on a routine clinical basis. The advantages to this approach include: 1) greater image contrast; 2) improved at depth spatial resolution; 3) three-dimensional data that can be readily intercompared with other imaging modalities; 4) cost-effective examinations; 5) quantifiable data; and 6) a procedure can be performed using currently existing radiopharmaceuticals in conventional dose ranges. As more institutions gain experience with this modality and newer radiopharmaceuticals, and as improvements in both hardware and software become more widely disseminated, the indications for this study and the subsequent number of procedures should continue to grow.

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