A comprehensive solution for extremity imaging

Philips BrightView XCT with Astonish

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Radionuclide bone scanning has been a mainstay in the noninvasive evaluation of bone disease for decades. While SPECT imaging provides better evaluation of abnormal tracer uptake than planar scintigraphy, it still produces less than ideal anatomic localization. The introduction of hybrid SPECT/CT devices such as BrightView XCT has added value in improved localization of skeletal lesions and improved characterization of the tracer uptake with the additional information from CT. This is especially important when evaluating peripheral bone disease, due to the complex anatomy and small structures involved.

This paper describes the innovative technologies that make BrightView XCT well-suited for extremity imaging. It also presents a variety of examples that demonstrate the clinical value of this unique system in this diagnostically challenging area.

Clinical drivers

Hybrid techniques such as SPECT/CT have been used clinically both for detecting malignant bone involvement as well as for non-oncologic bone scanning.[1-5] These include, for example, localization of infection or inflammation, evaluation of bone trauma such as occult fracture or stress fracture, and differentiating degenerative changes from more malignant processes. The combination of the highly sensitive SPECT study with the anatomic localization and characterization of skeletal lesions provided by CT allows for subtle, nonspecific abnormalities detected on bone scans to be interpreted as specific focal areas of pathology. Providing comprehensive morphological and functional information in a single study can improve diagnostic confidence and accuracy as well as providing information that is useful in determining appropriate clinical management.

One area where SPECT/CT imaging is proving to be particularly helpful is in extremity imaging. While stress fractures of the metatarsals or sesamoiditis can usually be identified with a single planar image, other pathologies may be more difficult to assess from planar images due to the complex anatomy and the small structures involved in the foot and ankle. The improved sensitivity of SPECT imaging [6, 7] coupled with a high-resolution CT image can be invaluable in this diagnostically challenging area.

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sense and simplicity

Being able to distinguish between stress fractures of the mid foot, degenerative joint disease in the mid foot and hind foot, osteochondritis dissecans, tarsal coalition, or other orthopedic pathologies is critical to patient management. Figure 1 shows an example where a patient was treated appropriately for inflammatory arthropathy of the right talonavicular joint rather than incorrectly for a stress fracture which may not have been appreciated without SPECT/CT. An added complication when evaluating patients with sports injuries is that many have had previous injuries resulting in anatomical abnormalities. This only amplifies the need for high-resolution anatomical images.

Similar diagnostic challenges occur when trying to evaluate hand and wrist pain. The American College of Radiology recommends MRI as the study of choice in patients with chronic wrist pain if routine radiographs are normal or nondiagnostic.[8] However, in a recent pilot study by Huellner et al., high-resolution SPECT/CT showed higher specificity than MRI (1.00 versus 0.20) in the evaluation of causative pathologies in patients with nonspecific pain in the hand or wrist.[9] And while MRI was more sensitive than SPECT/CT (0.86 versus 0.71), high-resolution SPECT/CT was shown to be a useful tool in the diagnostic work-up of the 21 patients included in the study.[9]

Diagnosis and management of diabetic foot infections is another area where SPECT/CT is making an impact. Foot infections are the most common problems in persons with diabetes. They are also one of the most common hospitalization causes and a major source of morbidity and resource utilization for diabetic patients. These individuals are predisposed to foot infections because of a compromised vascular supply secondary to diabetes. Local trauma or pressure (often in association with lack of sensation because of neuropathy), in addition to microvascular disease, can result in various diabetic foot infections ranging from simple cellulitis to chronic osteomyelitis. By providing a comprehensive view of both anatomy and specific disease processes in the foot, dual tracer SPECT/CT enables physicians to better diagnose diabetic foot infections and to select appropriate treatment for these diabetic patients.[10]

Orthopedic patients with infection surrounding surgical hardware also prove to be diagnostically challenging. Determining where the infection is relative to the bone, soft tissue, and hardware is critical in determining the appropriate patient management. This is another area where SPECT/CT can provide value. When necessary, dual isotope

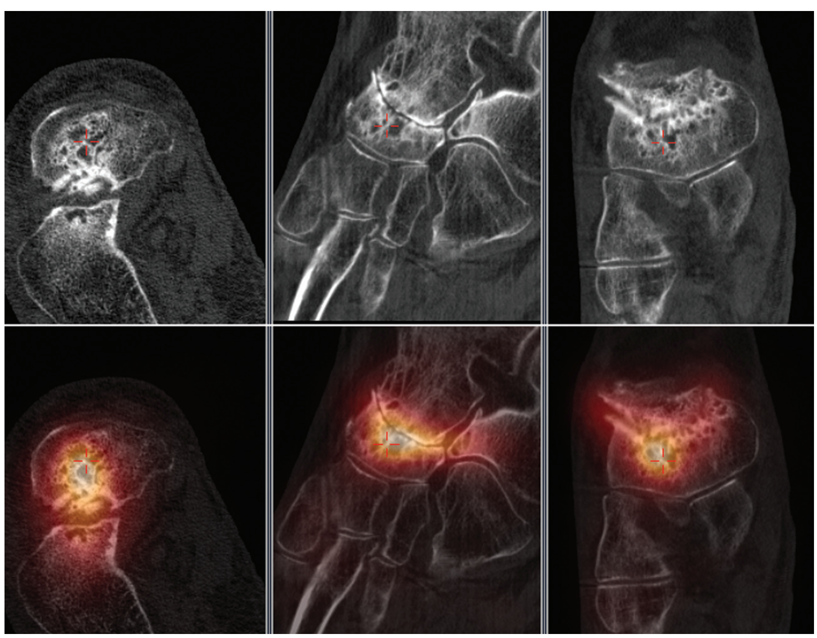

Figure 1 Tc-99m HDP SPECT/CT study performed on an 80-year-old patient with severe ankle pain and suspected stress fracture. BrightView XCT exam reveals markedly increased vascularity and delayed uptake in the hind foot and demonstrated intense uptake in right talonavicular region with severe degenerative change on low dose CT (subarticular cyst formation, joint narrowing and periarticular sclerosis).
Clinical data courtesy of Sydney X-Ray, Sydney, Australia

SPECT/CT can be performed, but in many cases the need for simultaneous bone scanning can be avoided by the CT fusion images. One such example is illustrated in Figure 2. In this case, a single examination on the BrightView XCT was able to rule out the important diagnosis of osteomyelitis, confirm soft tissue infection, and demonstrate an occult fracture as the source of pain in this patient. And while it was not necessary in this case, the combination of high quality anatomical images with functional information can be invaluable for surgical planning if such an intervention is required.

Because of its ability to localize pathology and aid in the planning of surgical interventions, SPECT/CT has revitalized interest in the use of nuclear medicine studies among orthopedists, radiologists, and surgeons. In order to get the most value when it comes to extremity imaging, the SPECT/CT system must be capable of providing high-resolution SPECT and CT images that are accurately registered to one another. BrightView XCT (Philips Healthcare, Cleveland, OH) is a compact variable-angle gamma camera with a high-resolution flat-panel X-ray detector system [11, 12] for localization and attenuation correction of SPECT data that provides these capabilities. The following sections describe the innovative technologies that make BrightView XCT an excellent choice for extremity imaging as demonstrated by the numerous clinical examples throughout this paper.

SPECT technologies

A good hybrid SPECT/CT system has to start with a good SPECT system. Because of the nature of imaging with parallel hole collimators, closer positioning enables higher resolution. BrightView XCT makes use of Philips CloseUp Technologies, such as BodyGuard automatic body contouring,[13] ZeroGap planar imaging, and an ultra-thin patient pallet, to keep the SPECT detectors closer to the patient during image acquisition.

A further technological advance that improves spatial resolution and SPECT image quality is the Astonish reconstruction algorithm.[14] Astonish is an iterative three-dimensional ordered subset expectation maximization (3D-OSEM) algorithm that incorporates depth-dependent resolution recovery into the reconstruction using the convolution method [15] to model the varying resolution as a function of distance from the detector. During the acquisition of SPECT data, the distance from the collimator to the center of rotation is recorded for each projection angle. During the reconstruction process, the amount of blurring is calculated based on these measured distances and the collimator response function. The counts are spread over multiple pixels during both the forward- and back-projection steps of the iterative reconstruction with the degree of broadening determined by the collimator response function and the distance between the pixel and the collimator. Furthermore, Astonish incorporates

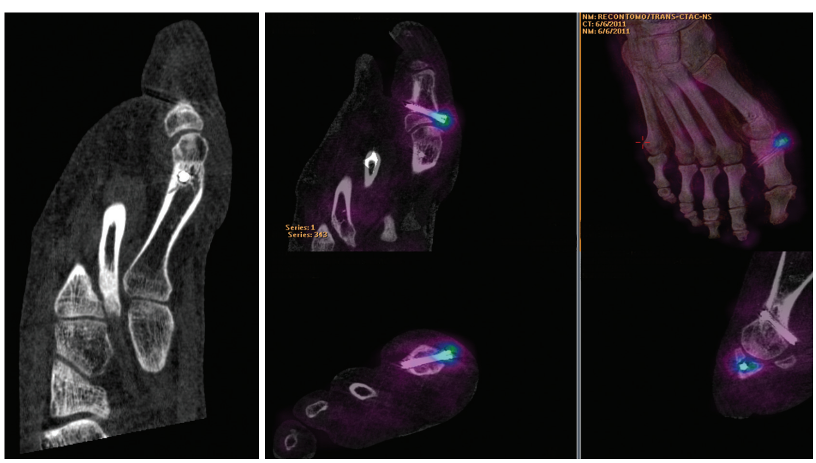

Figure 2 Tc-99m granuloscint SPECT/CT study of a 30-year-old female with persistent pain two months following surgery for hallux valgus. The SPECT/CT study was performed on the BrightView XCT to rule out osteomyelitis. White blood cell accumulation in the soft tissue surrounding the head of the screw was observed, indicating a soft tissue infection. Some bone resorption at proximal level of the screws, but no increased bone uptake and no interruption of the bony cortex excluded osteomyelitis. Straight radiolucent line at metaphysic of metatarsal bone marks the presence of a recent non-displaced transcortical fracture. Clinical data courtesy of Universitair Ziekenhuis Brussel, Brussels, Belgium

a proprietary matched dual filtering technique within the reconstruction process to control the accumulation of noise.[16] By performing the smoothing within the iterative process, Astonish can achieve exceptional noise suppression while preserving spatial resolution. With BrightView XCT, an attenuation map can be generated from the CT image [17] and Astonish can use this attenuation map to perform attenuation correction and scatter correction [18] in addition to resolution recovery.

Spatial resolution in the SPECT image becomes particularly important in the context of hybrid SPECT/CT imaging, since the physician can more confidently correlate the radiotracer uptake with anatomic features discernible in the CT image if the reconstructed activity distribution is well defined. Recently published articles by Livieratos et al. [19] and Knoll et al. [20] demonstrate the improvements in spatial resolution that can be achieved with Astonish. While these results are based on Tc-99m imaging, Astonish can also be used with other isotopes. Figure 3 provides an example of a Ga-67 image acquired on BrightView XCT and processed with Astonish. Note the high quality of the SPECT reconstruction and the correlation of the Ga-67 uptake with the pathologies in the first and second metatarsal perceptible in the CT images.

By incorporating the imaging physics into the reconstruction process and including a method to control noise, Astonish is less sensitive to counting statistics than more conventional reconstruction methods such as filtered back projection (FBP) or standard OSEM. Thus Astonish allows reconstructions with fewer counts without compromising image quality or diagnostic value.[19] The reduction in counts can result from a reduction in injected dose, when radioactivity supply is limited or concerns around patient exposure are paramount, or from a reduction in imaging time. Reducing imaging time can be essential in cases where patients have difficulty remaining motionless for extended periods of time, such as during hand or wrist imaging in the superman position (prone position with arms extended over the head).

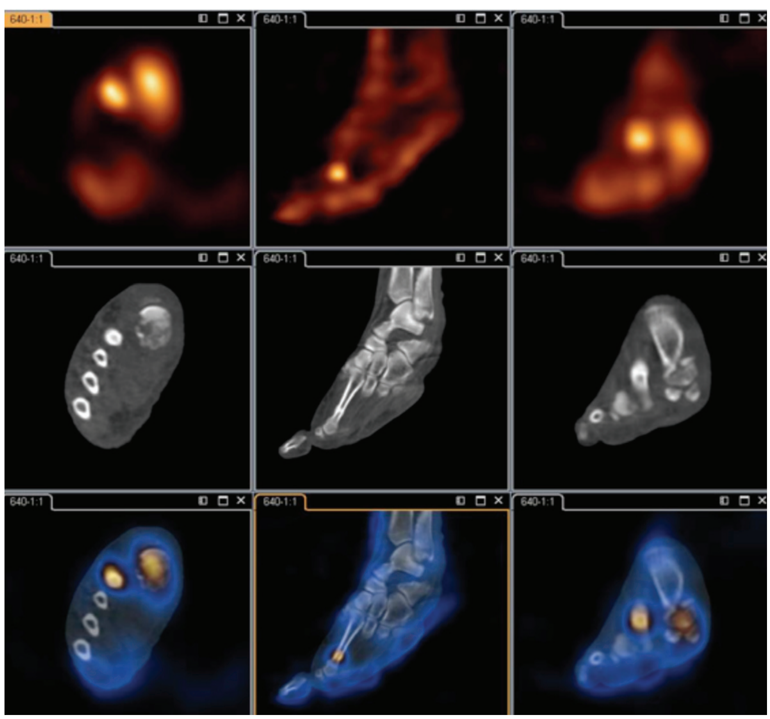

Figure 3 Ga-67 SPECT/CT images of a patient with osteomyelitis and non-union of the first metatarsal. Patient had prior bunionectomy of the first metatarsal that did not heal. Patient had a combined bone and gallium scan on BrightView XCT to rule out infection. The gallium scan shows uptake in the first metatarsal consistent with osteomyelitis and in the second metatarsal consistent with a stress fracture. Note the correlation of the gallium uptake in the second metatarsal with the thickening of the cortex bone discernible in the CT image.
Clinical data courtesy of Radiological Associates of Sacramento, Sacramento, CA

Another unique feature of the BrightView XCT SPECT system is the patented concurrent imaging technique [21] that provides the ability to create multiple data sets – each with independent matrix size, zoom, energy windows, gating parameters, stop criteria, and data type – from a single acquisition step. The acquired data is binned into multiple independent image sets based on the pre-defined acquisition protocol. Concurrent imaging offers more flexibility in acquisition protocols and provides additional information without requiring additional imaging time. One way to use concurrent imaging that may be beneficial for orthopedic applications is to simultaneously acquire full field and zoomed planar images, for example, imaging both hips/femurs in the full field image yet concurrently acquiring a zoomed hip/femur for better detail. This provides finer spatial sampling of the site of interest while simultaneously providing the contra-lateral side for comparison. Other ways to use concurrent imaging that may also be of interest in this area are to acquire simultaneously 128 × 128 matrix and 64 × 64 matrix SPECT data in low count studies or to acquire simultaneous dual isotope images (e.g., Tc-99m/In-111 or Tc-99m/Ga-67). Figure 4 presents an example of a simultaneous dual isotope study acquired with concurrent imaging on BrightView XCT that was instrumental in guiding the physician to the appropriate treatment for a patient presenting with ulcers on the right heel and left lower shin.

Finally, while this paper focuses mainly on SPECT/CT imaging, it's worth noting that SPECT imaging of the extremities may not always be feasible. For example, some patients may be unable to extend their arms over their head as required to acquire adequate SPECT images of their hands, wrists or elbows. In these cases, planar scintigraphy may be the only option. Fortunately, the BrightView XCT offers some unique features, such as ZeroGap planar imaging, flexible positioning of the SPECT detectors, and the ability to stow the X-ray flat panel into the gantry when not in use, that allow high quality planar images of the hands, wrists or elbows to be acquired with the patient in a comfortable seated position.

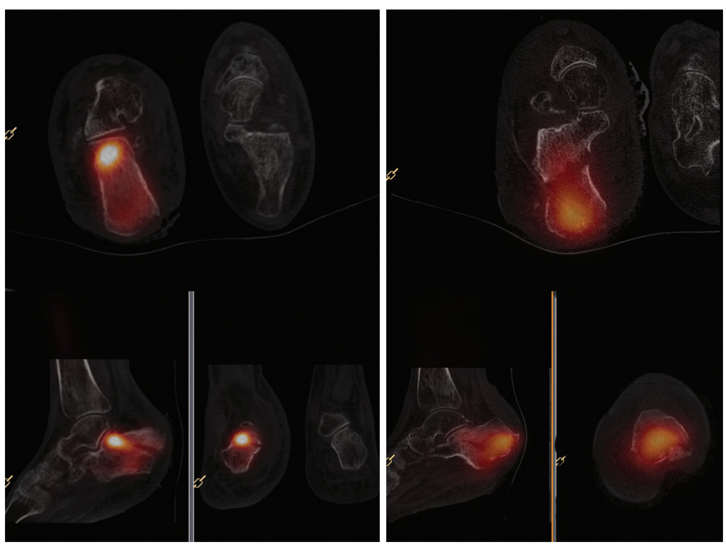

Figure 4 Simultaneous dual isotope study performed on an 80-year-old female with ulcers on right heel and left lower shin to rule out osteomyelitis. Tc-99m HDP bone scan (left image set) and Ga-67 scan (right image set) were acquired simultaneously on BrightView XCT using concurrent imaging. The bone scan is highly suspicious for osteomyelitis of right calcaneus inferiorly, but the gallium scan shows mild gallium uptake in calcaneum distinct from the HDP uptake region, excluding osteomyelitis. Antibiotics were changed to reflect a non-osseous infection.
Clinical data courtesy of Wollongong Nuclear Medicine, New South Wales, Australia

CT technologies

When it comes to SPECT/CT imaging of the extremities, high-resolution CT imaging is essential. Small focal abnormalities in the feet and ankles or hands and wrists must be well localized in order to make specific orthopedic diagnoses on the basis of their location. For example, the ability to localize activity within a bone or at an articular surface allows one to distinguish between fractures and joint disease. Furthermore, the radiographic appearance of a bone lesion may provide information that influences diagnosis and patient management. For example, rapidly growing aggressive metastases tend to be lytic (low density), whereas sclerotic (high density) metastases are considered to indicate a slower tumor growth rate.[1] Sclerosis may also be a sign of repair after treatment. Thus high-resolution CT can have a major advantage in the characterization of skeletal lesions by providing comprehensive morphological information that can impact therapeutic decision making. Figure 5 illustrates one example where, in the setting of post-surgical changes and lytic nature of the tumor, BrightView XCT helped to correctly identify tumor recurrence in new sites.

BrightView XCT uses a flat-panel cone-beam CT (CBCT) component mounted on the same rotatable gantry as the SPECT detectors to produce high-resolution CT images. The CBCT component consists of an X-ray source and a flat-panel X-ray detector shown schematically in Figure 6. The amorphous silicon flat-panel detector is based on similar technology as that used for digital X-ray detectors. X-rays are absorbed by an efficient cesium-iodide (CsI) scintillator that converts X-rays to light that can then be absorbed by the amorphous silicon detector. The detector pixel is very small (0.194 mm × 0.194 mm), which allows it to reproduce fine details in the object being imaged. The large active detector area (30 cm × 40 cm) consists of more than 3 million detector pixels arranged in rows and columns, as illustrated in Figure 6.

The high resolution of the flat-panel detector is a key feature that enables the projection data to be acquired isotropically, or evenly sampled in all directions. The advantage of this isotropic sampling is that image resolution is maintained when the data is viewed from

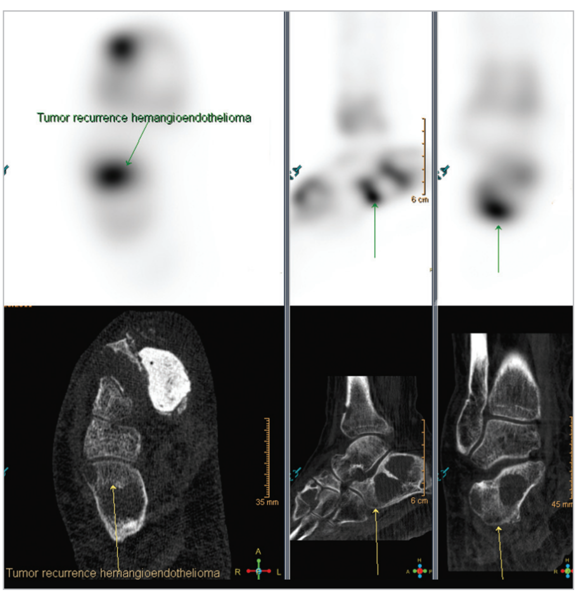

Figure 5 Tc-99m MDP SPECT/CT study performed on a 64-year-old female with resected hemangioendothelioma. Images were acquired on BrightView XCT post tumor resection involving proximal right tibia and right medial cuneiform. SPECT/CT revealed right-sided distal tibia and right calcaneum tumor recurrence in the periphery of the lytic lesions. Post-surgical inflammatory changes of proximal right tibia and medial cuneiform were also observed.

Clinical data courtesy of Washington Hospital Center, Washington DC

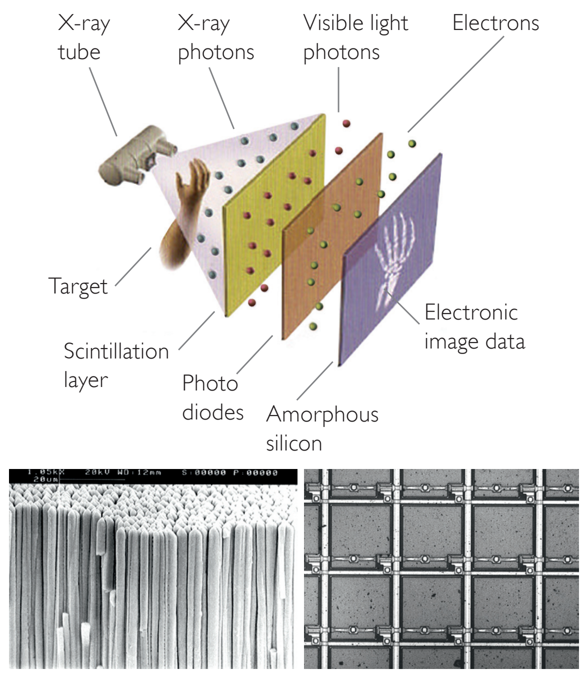

Figure 6 Schematic depiction of the X-ray imaging process with the flat-panel detector system (top image). Close-up of the cesium-iodide (CsI) scintillator layer (lower left image) that converts the X-ray photons to optical photons. Close-up section of the amorphous silicon detector (lower right image) that converts the optical photons to electric charge that forms the electronic image data. Each detector pixel is 0.194 mm × 0.194 mm.

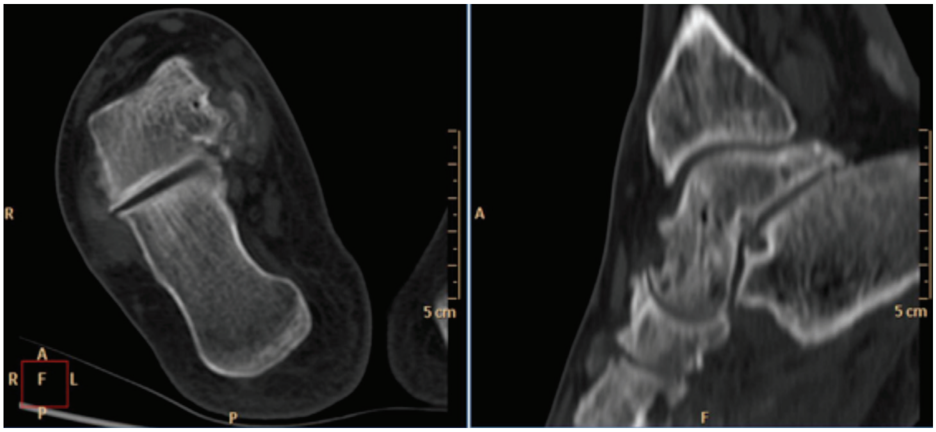

Figure 7 CT images of the foot acquired on a conventional spiral CT system. In-plane (transverse) pixel size is 0.75 mm × 0.75 mm and slice thickness is 3 mm. Note the degradation in observed spatial resolution in the sagittal view (right image) compared to the transverse view (left image) due to the anisotropic voxel size.

any angle. So unlike conventional spiral CT images which typically have poorer resolution in the sagittal and coronal views due to the thicker slices compared to the in-plane transverse pixel size (see Figure 7), XCT images viewed in the sagittal or coronal planes (or other oblique angles) have the same resolution as the transverse images because of the isotropic voxels. This is particularly important in extremity imaging since patient positioning constraints may dictate unusual display angles when imaging hands and feet as well as knee joints. It is also important in the context of SPECT/CT imaging since SPECT data also have isotropic voxels and are routinely reviewed in transverse, sagittal, and coronal views.

With a single 360° rotation of the BrightView XCT gantry, a 47 cm diameter transverse field of view (FoV) and a 14.4 cm axial length along the patient can be imaged with CT. Seven hundred and twenty X-ray projections are acquired for each spin during the 12- or 24-second rotation time, depending on the protocol. Extremity imaging is usually performed using the 24-second rotation speed since this protocol allows for a greater range of exposures and these areas are generally not affected by respiratory motion. The maximum dose for this protocol is 15 mGy, but given the low biological sensitivity to radiation of the extremities, this corresponds to an effective patient dose of only 0.5 mSv, assuming a k-value of 0.0023 mSv mGy^{-1} cm^{-1} (i.e., the k-value for the adult head) which should be a conservative estimate. This corresponds to approximately one tenth of the effective dose from the injected radiopharmaceutical used for the SPECT portion of the exam. Furthermore, the maximum CT dose is not always required; high-resolution CT images of the hands and wrists can be acquired with one quarter of this dose, as illustrated in Figure 8.

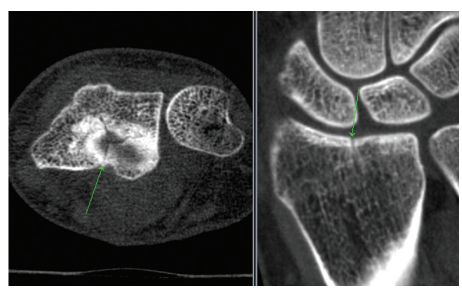

Figure 8 High-resolution, low-dose CT images of a 32-year-old female acquired with BrightView XCT ($CTDI_{VOL}$ = 3.75 mGy). Patient had chronic right wrist pain after distal radius fracture five months prior to SPECT/CT study. CT images reveal a star-like, residual, not yet fused fracture of the distal articular surface of the radius.
Clinical data courtesy of Cantonal Hospital Lucerne, Lucerne, Switzerland

The flat-panel system enables reconstruction with a 1 mm isotropic voxel size for the entire CT FoV and as small as 0.33 mm isotropic voxel size for a high-resolution sub-volume reconstruction from the same acquisition. Like other BrightView XCT case studies presented throughout this paper, the clinical value of this high-resolution isotropic imaging capability is demonstrated in Figure 9 through Figure 13. Figure 9 and Figure 10 are two examples where the high-resolution CT imaging capabilities of BrightView XCT allowed for the identification of fractures that were not observed with conventional CT or radiographs.

Figure 11 is an example where BrightView XCT provided information that allowed more aggressive orthopedic treatment with subsequent good outcome, while Figure 12 is a case that demonstrates that the quality of the high-resolution CT images provided by BrightView XCT can obviate the need for additional imaging studies, and Figure 13 is an example where these high-resolution CT images were used to plan a surgical intervention.

The studies discussed here clearly point out that the high-resolution CT images provided by BrightView XCT can improve the characterization of indeterminate bone lesions, and the additional CT information influences patient management.

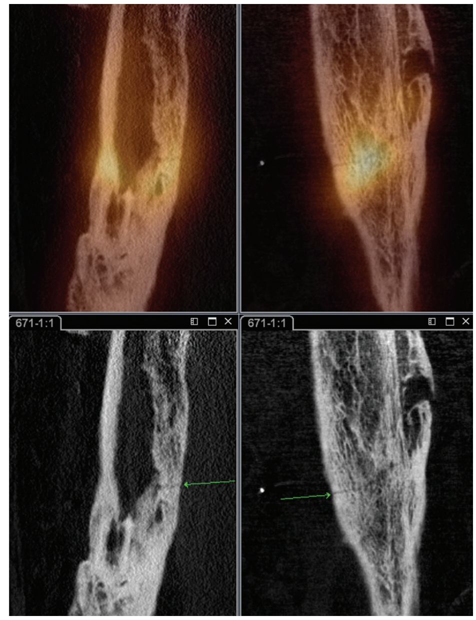

Figure 9 Tc-99m DPD SPECT/CT study performed on a 65-year-old male with traumatic fracture of right thigh with osteomyelitis 2.5 years prior to exam. Status post several curettages and reconstruction with bone replacement with new onset of pain. BrightView XCT study was performed when X-rays and conventional CT did not identify new pathology. SPECT/CT study revealed very fine fracture/fissure line seen on CT with high bone-agent uptake directly around this fracture line identifying a new insufficiency fracture/fissure within the formerly fractured and infected area of the right thigh. Patient subsequently underwent surgery to receive a new femoral osteosynthesis.
Clinical data courtesy of Cantonal Hospital Lucerne, Lucerne, Switzerland

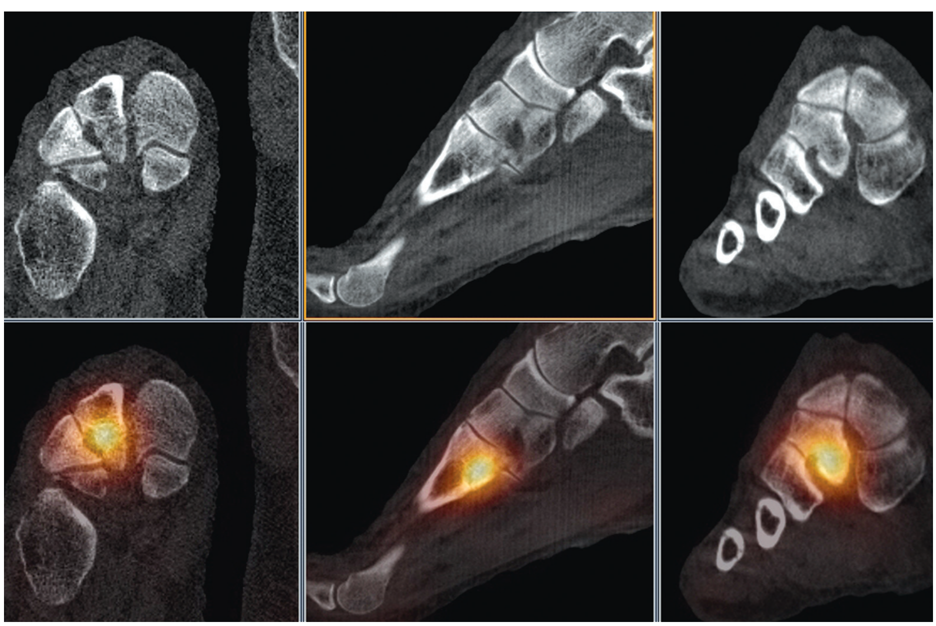

Figure 10 Tc-99m HDP SPECT/CT study of a 64-year-old female with right midfoot pain for one week. BrightView XCT study was performed when no evidence of fracture was observed on radiographs. SPECT/CT study revealed acute fracture of base of second right metatarsal.
Clinical data courtesy of Sutherland Nuclear Medicine, Sydney, Australia

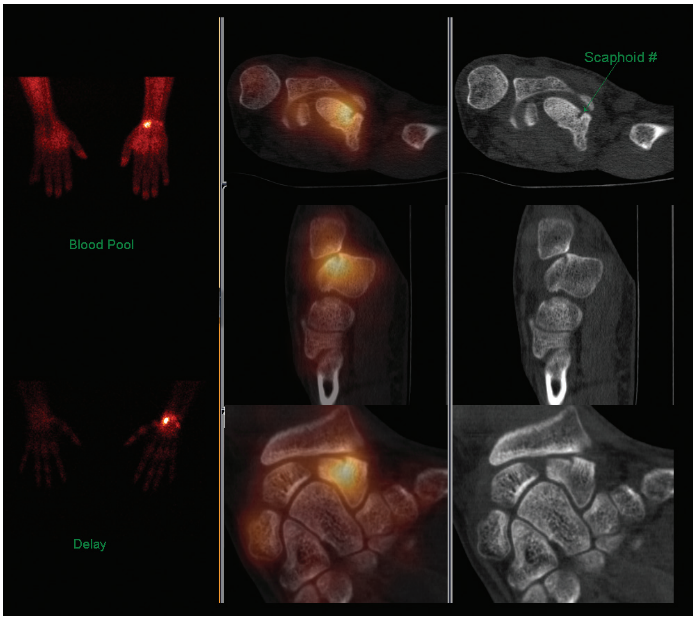

Figure 11 Tc-99m MDP SPECT/CT study performed on a 22-year-old male 12 weeks post scaphoid fracture due to continued tenderness. BrightView XCT study confirmed scaphoid fracture with incomplete union. After more aggressive orthopedic treatment, fracture healed and patient is symptom-free. Clinical data courtesy of The Royal Wolverhampton Hospitals NHS Trust, Surrey, UK

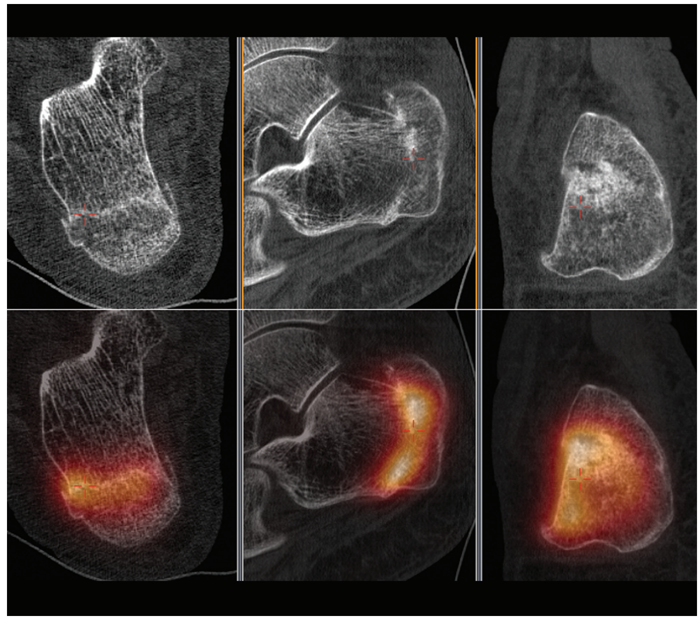

Figure 12 Tc-99m HPD SPECT/CT study performed on a patient with right heel pain for a few months. BrightView XCT study revealed intense uptake in right calcaneus along a fracture line posteriorly in the CT, which also demonstrated malalignment and impaction of the fracture. Patient was managed appropriately for the stress fracture and orthopedic review was arranged to assess the malalignment of the fracture. No further imaging was required. Clinical data courtesy of Sydney X-Ray, Sydney, Australia

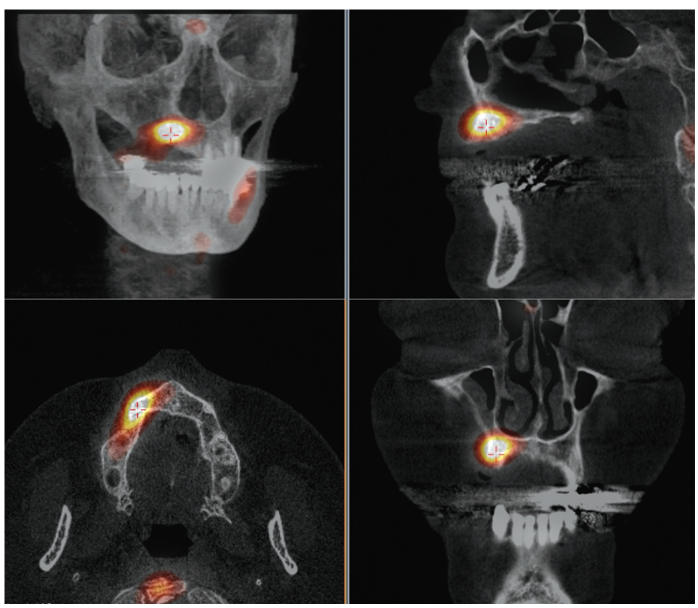

Figure 13 Tc-99m DPD SPECT/CT study performed on a 60-year-old female with metastasis from breast cancer. Patient was imaged with BrightView XCT one year after bisphosphonate-associated osteonecrosis in the maxilla region to evaluate for osteomyelitis and to plan for further surgical intervention. BrightView XCT images provided accurate localization of persistently increased bone metabolism compatible with osteonecrosis or osteomyelitis in the jaw and appropriate planning of the extent of surgery to reconstruct the affected area. Clinical data courtesy of Inselspital Bern University Hospital, Bern, Switzerland

System considerations

The BrightView XCT, with its flat-panel-based CBCT component, presents a unique SPECT/CT system that is well suited for extremity imaging. The large gantry aperture provides an open patient experience during the CT scans. Keeping the patient relaxed and comfortable during imaging can help reduce unwanted patient motion, both during and between scans.

Because the CBCT component is mounted on the same rotatable gantry as the SPECT detectors, the CT and SPECT images can be acquired with little or no table translation between the two scans. This coplanar design reduces the misalignment between the CT and SPECT images since there is little opportunity for misalignment due to bed motion or differential table sag between the SPECT and CT imaging positions. Accurate alignment of the two image sets is critical when trying to localize the radiopharmaceutical uptake in the SPECT images to the anatomy visualized in the CT images, as illustrated in Figure 14. Due to the well-localized activity distribution within the SPECT image, the high spatial resolution of the CT image, and the accurate registration of the two image sets, the physician was able to definitively localize the fibula injury to the growth plate rather than an adjacent area. Furthermore, the relatively short scan time of the SPECT/CT study (in comparison to multiple pinhole views) was more comfortable and bearable for this very young patient. Figure 15 shows another example where accurate correlation of focal radionuclide activity to the joint spaces rather than bony structures allowed the patient to be treated for an inflammatory etiology rather than the fracture that was initially suspected.

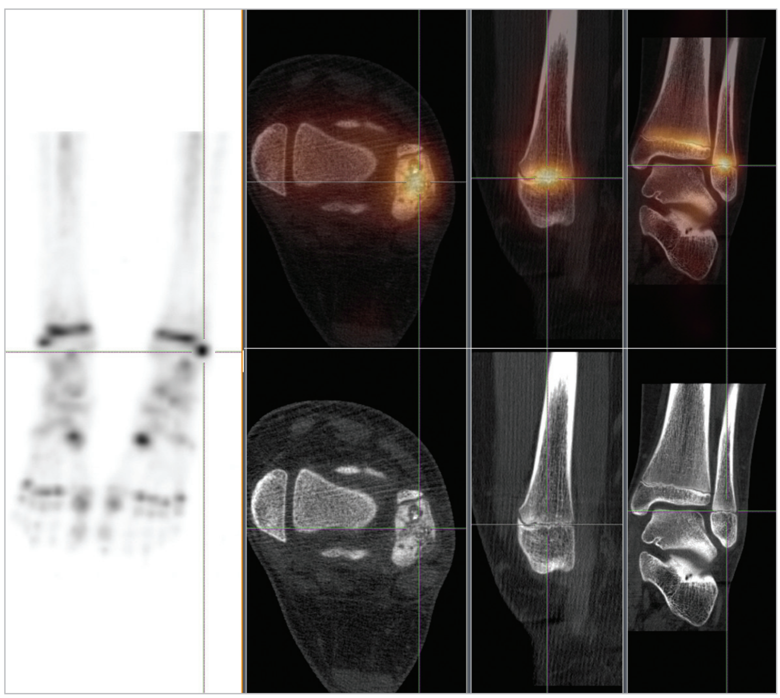

Figure 14 Tc-99m HDP SPECT/CT study of an 11-year-old female with anterolateral pain on weight-bearing after fall with left ankle inversion. BrightView XCT exam reveals low-grade left distal fibula growth plate fracture and low-grade left talar head contusion. Clinical data courtesy of Sutherland Nuclear Medicine, Sydney, Australia

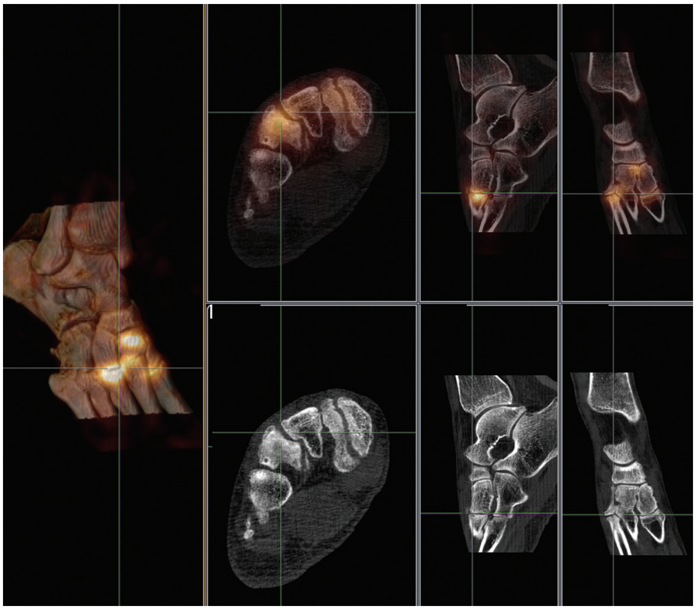

Figure 15 Tc-99m HDP SPECT/CT study of a 43-year-old female patient with right foot pain, status post trauma. BrightView XCT study was performed to assess for possible fracture. SPECT images revealed multiple foci (at least three) of activity within the mid-portion of the right foot that correlated to the joint spaces on CT images. No evidence of fracture or activity correlated to bony structures was observed.
Clinical data courtesy of Washington Hospital Center, Washington, DC

Another advantage of the unique co-planar design of the BrightView XCT is that the system has a smaller footprint and system weight compared to SPECT/CT systems that use a separate CT gantry. The compact design allows the system to fit into a standard nuclear medicine-sized room, which can help reduce installation costs. Furthermore, an in-room CT control option allows the operator to remain in the room and closer to the patient, and avoids the costs associated with a separate control room. With a design that's tailored towards nuclear medicine, the BrightView XCT brings all the capabilities of the BrightView SPECT system together with a flat-panel CBCT component that provides low-dose, high-resolution CT images with isotropic voxels. SPECT/CT planning is done from the nuclear medicine p-scope, as simple as planning for a SPECT-only procedure.

Summary

High-resolution CT integrated with SPECT offers a major advantage in the characterization of peripheral bone disease. It improves diagnostic confidence and therapeutic decision making by providing comprehensive morphological and functional information in a single study. BrightView XCT with Astonish provides a comprehensive solution for SPECT/CT imaging of the extremities. The unique flat-panel X-ray detector system provides high-resolution CT images with isotropic voxels. Concurrent imaging offers more flexibility in acquisition protocols and provides additional information without requiring additional imaging time. Astonish provides improved SPECT resolution and the ability to process lower count data without compromising image quality. The unique coplanar design of the gantry is compact, yet offers an open patient experience for better comfort and compliance. Moreover, the coplanar design reduces the risk of misalignment between the SPECT and CT images. Together, these features create a hybrid SPECT/CT system that is ideally suited for the evaluation and management of patients with peripheral bone disease.

Acknowledgements

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