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Review article

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Review of the role of bone-SPECT/CT in tarsal coalitions

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Tarsal coalition (TC) is a congenital abnormal connection (fibrous, cartilaginous, or osseous) between two or more bones in the hind and midfoot, mostly consisting of calcaneonavicular or talocalcaneal coalition, and is often asymptomatic. However, TCs may result in foot motion limitation and pain with or without flatfoot (pes planus), arising in adolescents and young adults. Appropriate imaging is needed to pinpoint foot pain in the (suspected) TC, starting with plain radiographs. Still, normal radiographs do not exclude TCs. Computed tomography (CT) and MRI are frequently used advanced imaging techniques. CT alone has known limited sensitivity in cartilaginous and fibrous TCs and correlation between CT abnormalities and pain may be challenging, as solely anatomical changes in TCs are often asymptomatic. MRI can depict soft tissue abnormalities in TC with high accuracy. Nonetheless, after the implantation of metallic osteosynthesis material, MRI is often limited due to image distortion, signal loss, and misregistration. Bone scintigraphy with [99mTc]Tc-diphosphonate single photon emission computed tomography/CT (bone-SPECT/CT) is a known sensitive tool to detect osteoblastic bone pathology. However, the literature concerning bone-SPECT/CT in TC patients is limited. This article reviews bone-SPECT/CT patterns in TCs, how it complements other imaging techniques and their relation to clinical complaints. Bone-SPECT/CT excels in accurate bone pathology characterization in TC, confidently excluding synchronous lesions elsewhere, and offering optimal insight into osseous structures and 3D-localization of bone metabolism for surgery planning. Furthermore, even with implanted osteosynthesis material, bone-SPECT/CT can pinpoint the culprit pain generator, where MRI is either contra-indicated or considerably hampered. *Nucl Med Commun* 44: 115–130 Copyright © 2022 Wolters Kluwer Health, Inc. All rights reserved.

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Background

Tarsal coalition is an abnormal congenital connection (fibrous, cartilaginous, or osseous) between two or more bones in the hind- and midfoot, which may result in limitation of foot motion and development of pain [1]. Tarsal coalitions are also known to be the cause of painful flatfoot (pes planus) in adolescents and young adults [1,2]. The vast majority consists of calcaneonavicular (CNC) or talocalcaneal coalitions (TCCs) and are often asymptomatic. In patients with complaints of pain, appropriate imaging is needed for definite diagnosis, starting with plain radiographs of the foot. In insufficiently explained symptomatic patients, advanced imaging using computed tomography (CT), bone scintigraphy with [^{99m}Tc]Tc-diphosphonate single photon emission computed tomography/CT (bone-SPECT/CT), or MRI may more precisely characterize the condition in either primary diagnosis or during follow-up, guide in surgical approach, and thus improve patient care. Specific literature is still limited about findings on bone-SPECT/CT in patients with tarsal coalitions; however. This article reviews the characteristics and patterns of bone-SPECT/CT in patients with tarsal coalitions and in relation to clinical complaints and to other imaging techniques.

Design and aims

Publication design

Evidence-based review of the value of bone-SPECT/CT in tarsal coalition in relation to clinical symptoms, outcome, and its role compared to radiological features on plain radiographs and MRI for the three types of tarsal coalitions (fibrous, cartilaginous, or osseous) and for the two most anatomically prevalent tarsal coalitions (calcaneonavicular and TCC). This review is illustrated with cases typical for tarsal coalition patients' clinical

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management from an academic hospital with specialized foot surgery with consecutive plain radiographs, MRI, and high-resolution/quality bone-SPECT/CT images to exemplify the additional value of bone-SPECT/CT compared to other modalities.

Compliance with ethical standards

Ethical approval and consent to participate and publication: the ethics committee has officially waived informed consent for this review (reference number 2022-00121).

Clinical context and dilemmas

In tarsal coalition, the bridge between the bones is initially fibrous, then gradually becomes cartilaginous, and might eventually ossify. In symptomatic tarsal coalition patients, pain complaints usually arise at 8–16 years of age, around the time of ossification of the coalition [3].

Commonly, nonoperative/conservative treatment is effective and can prevent surgery (79% in calcaneonavicular and 62% in TCC) or delay the need for operation [4]. Conservative treatment consists of intermittent immobilization using a walking boot for six weeks, followed by supportive measures (longitudinal arch supports with ankle strengthening), continuous immobilization via casting or orthopedic footwear, nonsteroidal anti-inflammatory medications, intra-articular steroid injection, or activity modification [4,5]. Tarsal coalition may result in a rigid flat foot deformity (pes planus). The differential diagnosis of rigid flat foot deformity includes tarsal coalition, neurogenic planovalgus, and peroneal spasticity [6]. Pediatric or adolescent ankle pain is often initially mistaken for a common ankle sprain in the initial evaluation, while an underlying tarsal coalition or other pathology, such as juvenile idiopathic arthritis, osteochondritis dissecans of the talus, hereditary sensory-motor neuropathy, or transitional ankle fractures, might be the true cause [2].

Surgery may involve resection for both calcaneonavicular and TCC and for large TCC fusion may be considered including concomitant planovalgus reconstruction [4,6]. In the case of indicated operative treatment, effective pain reduction benefits from pinpointing the culprit pain generator site, which impacts the choice of therapeutic intervention.

Conventional imaging in tarsal coalitions, including issues and limitations

In patients presenting with foot pain, appropriate imaging is needed for definitive diagnosis, starting with plain radiographs of the foot [7]. In fibrous coalitions, irregularity and narrowing of the bony interfaces can be seen, often with associated sclerosis or unusual orientation of the articulation. In the case of calcaneonavicular, radiographs should include 45 degrees oblique and lateral views [7]. Although the anteater nose sign, which is the extension of the anterior process of the calcaneus beyond the calcaneocuboid joint on radiographs (Fig. 1), is highly

Fig. 1

Sixteen-year-old female patient with exercise-induced pain in both feet (predominantly left side) subsequent to a trauma that occurred around 11 months prior to the initial imaging. Plain radiographs of the left foot: 45 degrees oblique (left panel) and lateral view (right panel) show an extension of the navicular bone to posterolateral, approximating the anterior process of the calcaneus (known as the reversed anteater nose sign) with irregularity and narrowing of the bony interface between calcaneus and navicular, as well as associated sclerosis. On the lateral view, note a (modest) anterior tubular elongation of the superior calcaneus which approaches the navicular bone (known as the classical anteater nose sign). Therefore, these plain radiographs depict a combination of the classical and reversed anteater nose sign, consistent with a non-osseous calcaneonavicular.

specific for calcaneonavicular with specificity of 94% [7], plain radiographs do not exclude a calcaneonavicular due to the limited sensitivity of 72% [7]. Especially TCC may demonstrate a bony bar in a bony coalition and short neck of the talus or 'beaking', being the radiological superior projection of the distal aspect of the talus on plain radiographs (Fig. 2, red circle) [8]. Comparable results with plain radiographs are noted for the CN bar in calcaneonavicular with excellent specificity of 100%, but limited sensitivity of (73%) [7]. Thus, normal radiographs do not exclude this type of tarsal coalition.

For plain radiographs in suspected TCC, the X-ray beam needs to be angled between 35 and 45 degrees as the patient stands on the cassette, also called the Harris projection [9]. Even then, the TCCs may be hard to visualize using plain radiographs. Sensitivity of plain radiographs for the most specific findings for TCC varies considerably in the literature [3,7,9–11]. The C-sign, a C-shaped line formed by the outline of the talar dome and the inferior margin of the sustentaculum tali on lateral projections (see Figs. 2 and 3, blue arrows on the lateral view), has reported sensitivity ranging from 40% to 97% and mediocre sensitivity for the talar beak of 53% (see Figs. 2 and 3, red circle on the lateral view and a narrowed irregular joint space on the 45° view) [3].

Other studies found a 20% incidence of C-sign in patients who had a flatfoot deformity but no tarsal coalition [7,11]. Therefore, especially in suspected TCC, additional advanced imaging would logically have incremental value over plain radiographs.

Computed tomography (CT) displays the anatomical changes in tarsal coalitions of especially bone, with straightforward abnormal osseous continuity in osseous coalitions and more subtle changes in fibrous and cartilaginous coalitions by using cross-sectional imaging. In calcaneonavicular, CT will often reveal a narrowed space between the calcaneus and navicular, with elongation of the anterior process and a hypertrophic distally, squared bony surface (anteater nose sign). Cartilaginous tarsal coalitions may mimic osteoarthritis with space narrowing, mild sclerosis (eburnation), and subchondral cysts in an otherwise normal foot without other sites of osteoarthritis [8]. CT alone also has known limited sensitivity in cartilaginous and fibrous tarsal coalitions [12]. Moreover, it is noteworthy that the correlation between the changes in CT and pain complaints may be challenging as solely anatomical changes in tarsal coalitions are often asymptomatic.

MRI can be useful for the characterization of (suspected) tarsal coalition, with especially high accuracy for soft tissue abnormalities [8,12]. In osseous tarsal coalitions, an abnormal osseous continuity with bone marrow signal (high signal on T1-weighted images, low signal on T2-weighted fat-suppressed images) is seen as similar to the normal bone [8]. Cartilaginous tarsal coalitions will often demonstrate intermediate- to hypointense signal on T1-weighted images (both similar to cartilage) and a combination of bone marrow edema together with intermediate signal on T2-weighted images with fat saturation [8]. Fibrous tarsal coalitions, on the other hand, will often display a hypointense signal on both T1- and T2-weighted images. Specificity in discriminating cartilaginous from fibrous tarsal coalitions may be limited, although (as is the case with other modalities). Some, therefore, proclaim to merely aim to discriminate between a non-osseous or osseous tarsal coalition [8].

In calcaneonavicular, MRI, may demonstrate a hypointense band (Fig. 4b, middle images) between the calcaneus and navicular bone with an irregular surface of the articulating bones and adjacent bone edema on sagittal T1-weighted sequences (Fig. 4b, middle images). On T2-weighted sequences with fat suppression Fig. 4b, the image on the right), a hypointense band at the site of the calcaneonavicular is seen with accompanied adjacent bone marrow edema. The hypointense signal on both the

Fig. 2

Lateral plain radiographs demonstrating a C-sign (blue arrows), a C-shaped line formed by the outline of the talar dome and the inferior margin of the sustentaculum tali on lateral projections suggestive of TCC. SPECT/CT showing partially fused TCC (posterior facet) with increased uptake in the non-fused area, indicating the likely pain generator region. CT, computed tomography; TCC, talocalcaneal coalitions.

sequences is consistent with a fibrous calcaneonavicular (Fig. 4b). Performance of MRI in tarsal coalitions is often described as very effective, with generally excellent sensitivity. Although radiology can identify bony coalitions (plain radiographs, CT) and cartilaginous and fibrous coalitions (MRI), pinpointing the precise origin of pain complaints may be challenging [8,13]. Moreover, in post-surgical tarsal coalitions including metallic implants, the use of MRI is often limited due to image distortion, signal loss, and misregistration [14].

In foot and ankle pathology, some literature has emerged with promising results for bone-SPECT/CT [15]. However, specifically in patients with tarsal coalitions, the exact role of bone-SPECT/CT in clinical work-up and relation to other (radiological) imaging modalities is still unknown.

Molecular and multimodality imaging in tarsal coalitions

Bone scintigraphy including bone-SPECT using [^{99m}Tc]Tc-diphosphonate agents sensitively image in-vivo osteoblast activity with high sensitivity for early detection of pathophysiological changes of bone remodeling, before anatomical changes occur [16]. The CT component of bone-SPECT/CT is useful as it not only improves the signal of bone-SPECT by attenuation correction, it also localizes the focus of increased [^{99m}Tc]Tc-diphosphonate uptake precisely, and in longer-existing pathology, the CT may reveal the anatomical changes and in this way improve the specificity of the finding.

Bone-SPECT/CT is an established problem-solving modality in patients with foot and ankle pathology, with high sensitivity for the detection of osteoblastic activity in various bone and joint diseases and with a generally high correlation of osteoblastic activity to pain complaints in many bones and joint disorders [15]. However, specific literature is still limited about findings on bone-SPECT/CT in patients with tarsal coalitions, with one specific case report that we are aware of [17], and the rest being more generalized overviews on foot and ankle pain, without specific focus on tarsal coalitions [15,18–20] or with little consideration of molecular imaging [7,8,14]. The role of bone-SPECT/CT in tarsal coalitions has not yet been described in a review format in relation to other imaging techniques and clinical outcomes.

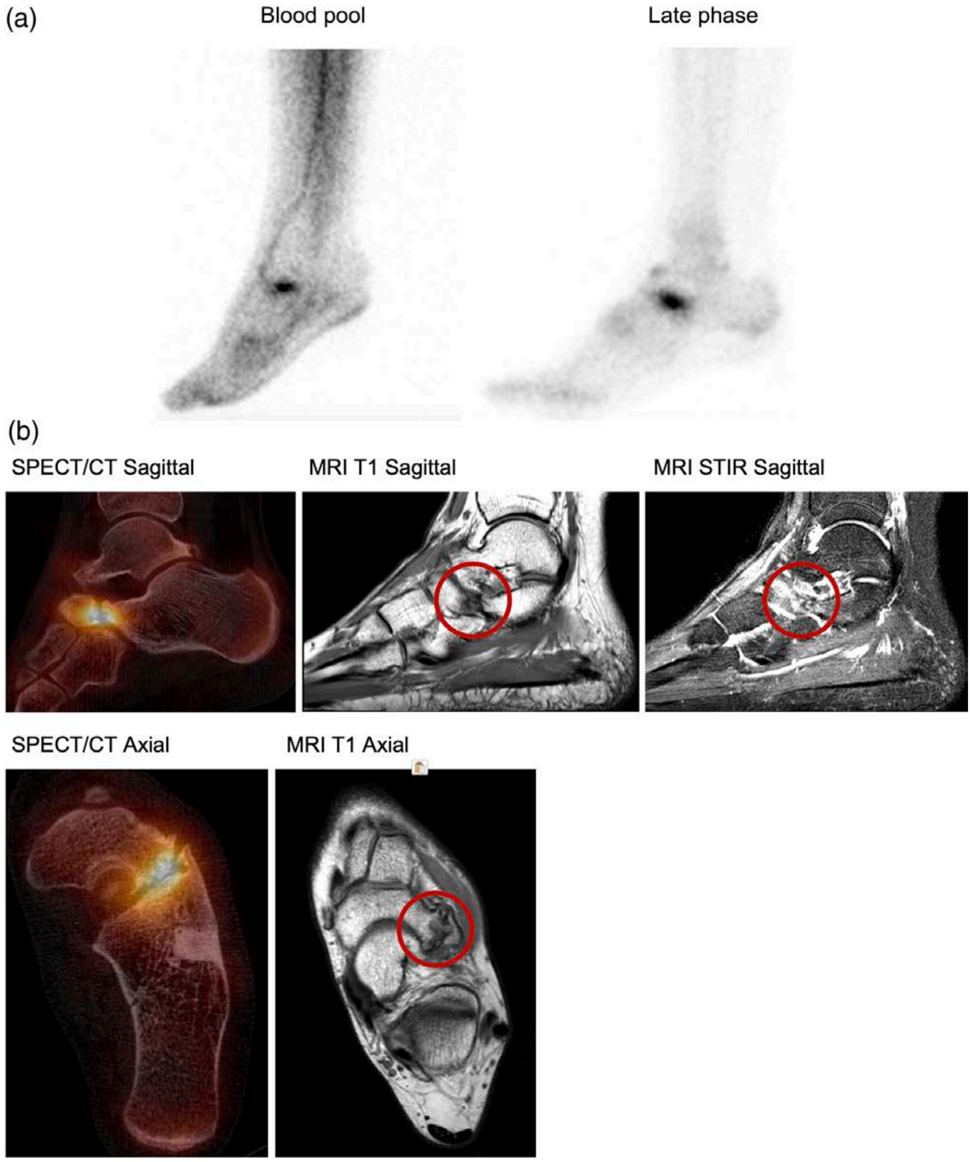
On bone scintigraphy, a tarsal coalition is usually projected on early phase imaging 5 min post-injection as focal increased [^{99m}Tc]Tc-diphosphonate activity in the region of the hind- and midfoot indicating increased focal blood pool, followed 4 h later post-injection by focal strongly increased bone turnover in the same area in an otherwise normal uptake pattern elsewhere (Fig. 4a).

Lastly, also positron emission tomography with integrated computed tomography using sodium fluoride-18

Fig. 3

Plain radiographs: strongly suggestive of TCC in the left foot with a C-sign (blue arrows) and a prominent talar beak (i.e. a superior projection of the distal aspect of the talus, red circle) on the lateral view and a narrowed irregular talocalcaneal joint space on the 45° view. TCC, talocalcaneal coalitions.

Fig. 4



Same 16-year-old female patient as in Fig. 1. (a) Image on the left with planar blood pool (early) phase bone scintigraphy of the left ankle and foot with increased blood pool in the left tarsus and image on the right with planar late (mineralization) phase with increased bone turnover in the left tarsus. (b) Images on the left bone-SPECT/CT of the left ankle (upper image sagittal, lower image transverse) with clear localization of increased bone turnover in a non-osseous calcaneonavicular. MRI in the same patient MRI, demonstrating a hypointense band at the non-osseous calcaneonavicular and adjacent bone edema on sagittal T1-weighted sequences (middle images). On T2-weighted sequences with fat suppression (image on the right), a hypointense band at the site of the non-osseous calcaneonavicular with accompanied adjacent bone marrow edema. The hypointense signal on both sequences is consistent with a fibrous calcaneonavicular. CT, computed tomography.

(Na[^{18}F]F PET/CT) is able to image bone turnover in bone and joint disease, which works in several ways similar to bone-SPECT/CT [16,21], but this technique is outside the scope of the current article.

Types of tarsal coalitions and imaging

Non-osseous calcaneonavicular

In calcaneonavicular, the increased bone turnover on planar scintigraphy is located in the lateral aspect of the articulation between hind- and midfoot. The location and pattern on planar bone scintigraphy should usually already be strongly suggestive of a calcaneonavicular (Fig. 4a). In TCC, the increased bone turnover on planar scintigraphy is expected laterally in the hindfoot. Still, the uptake itself is non-specific and could also be attributed to other diseases, such as a fracture, severe unifocal inflammatory arthritis, or to osteoarthritis with considerable reactive inflammation. Bone-SPECT/CT images may improve specificity, in calcaneonavicular the CT part will often show the anteater nose sign, as well as an irregular surface of the articulating bones, and subchondral cysts. A clear increased bone turnover at the site of the calcaneonavicular is usually present, the absence of increased bone turnover elsewhere in the foot excludes other active pathologies.

All the cross-sectional techniques (CT, MRI, and bone-SPECT/CT) depict the extent of the tarsal coalition more precisely than plain radiographs (Fig. 4b). Moreover, MRI is better equipped to depict the adjacent soft tissue structures, and bone-SPECT/CT excelling in the fast and accurate characterization of the bony pathology and excluding any synchronous pathology elsewhere in the foot and ankle. Bone-SPECT/CT is often able to ascertain (non-osseous) calcaneonavicular to be the very likely pain generator because of the focal increased bone turnover and is accurate to exclude any other active bone pathology in the feet or ankles with high confidence.

Partly ossified calcaneonavicular

Although MRI is generally useful in patients with partly ossified calcaneonavicular, MRI (Fig. 5) might not always delineate the ossified fragment as clearly as on bone-SPECT/CT (Figs. 6 and 7), with just generalized edema in this area (Fig. 5, green circle). The increased bone turnover on SPECT combined with the more precise anatomic information of the CT part of the bone-SPECT/CT might therefore be advantageous in surgical planning. Figures 6 and 7 demonstrate the value of bone-SPECT/CT in adequately combining the pathophysiological information with precise anatomical localization in a patient with calcaneonavicular. Bone-SPECT/CT pinpoints the pain generator and excludes other osseous painful sites which allow improved planning for diagnostic or therapeutic injections and surgical procedures, such as resection of a partly ossified calcaneonavicular coalition (Fig. 8).

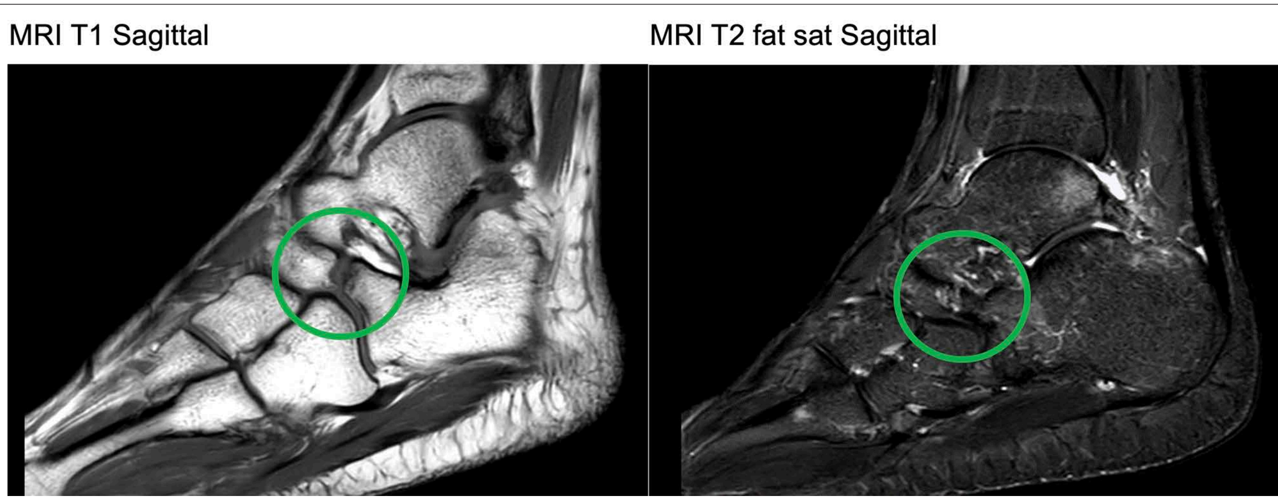
Completely ossified calcaneonavicular

Complete osseous calcaneonavicular may be visualized using plain radiographs, typically with a calcaneonavicular bone bar and flat foot deformity (pes planovalgus) on lateral projection (Fig. 9, red circle). MRI will often show

Fig. 6

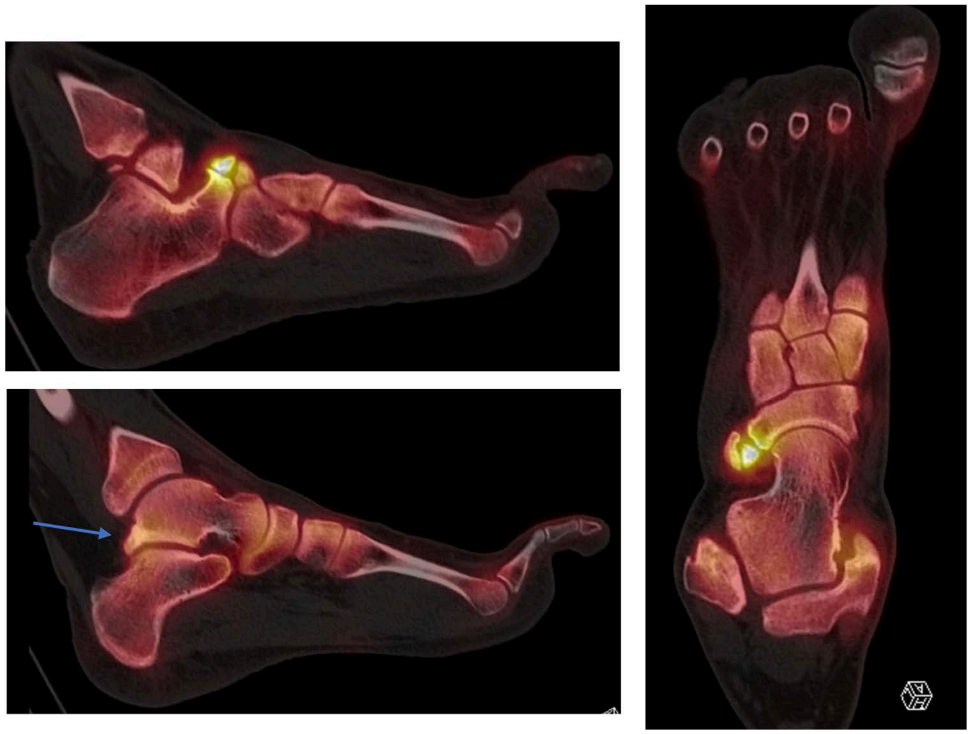
SPECT/CT with 3D volume rendering with maximum intensity projection was of incremental value as the low-dose CT depicted the partially ossified coalition, with increased bone turnover at the calcaneonavicular articulation on SPECT. Also note the increased bone-turnover on the dorsal side of the left ankle joint as an additional finding (blue arrow), caused by an os trigonum, on this projection optimized for the calcaneonavicular the os trigonum is obscured by the fibula; however. CT, computed tomography.

Fig. 5



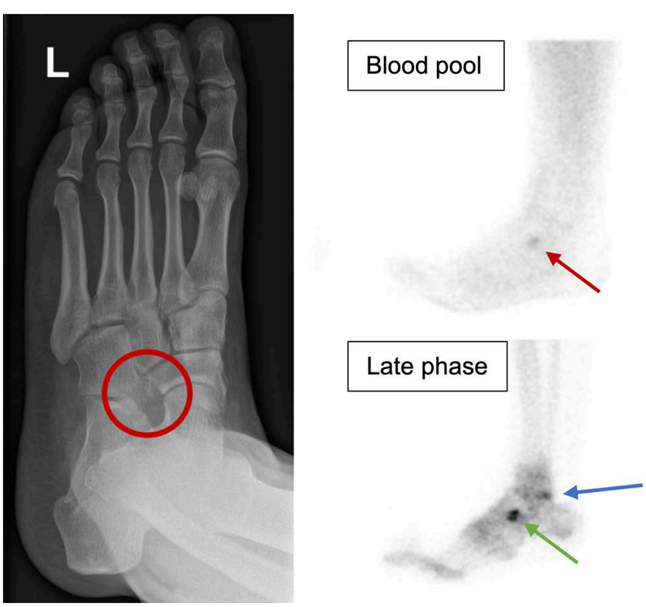
Ninteen-year-old male patient, with midfoot pain on the left and the presence of calcaneonavicular: MRI showed the calcaneonavicular with moderate bone-marrow edema (T2 fat saturation); however, with no clear visualization of the ossified fragment with this modality.

Fig. 7



The cross-sectional bone-SPECT/CT of the same patient as Fig. 5 more precisely depicts the partially ossified coalition, with increased bone-turnover at the calcaneonavicular articulation as well as increased bone-turnover on the dorsal side of the left ankle joint as an additional finding, caused by an os trigonum (blue arrow). CT, computed tomography.

Fig. 8

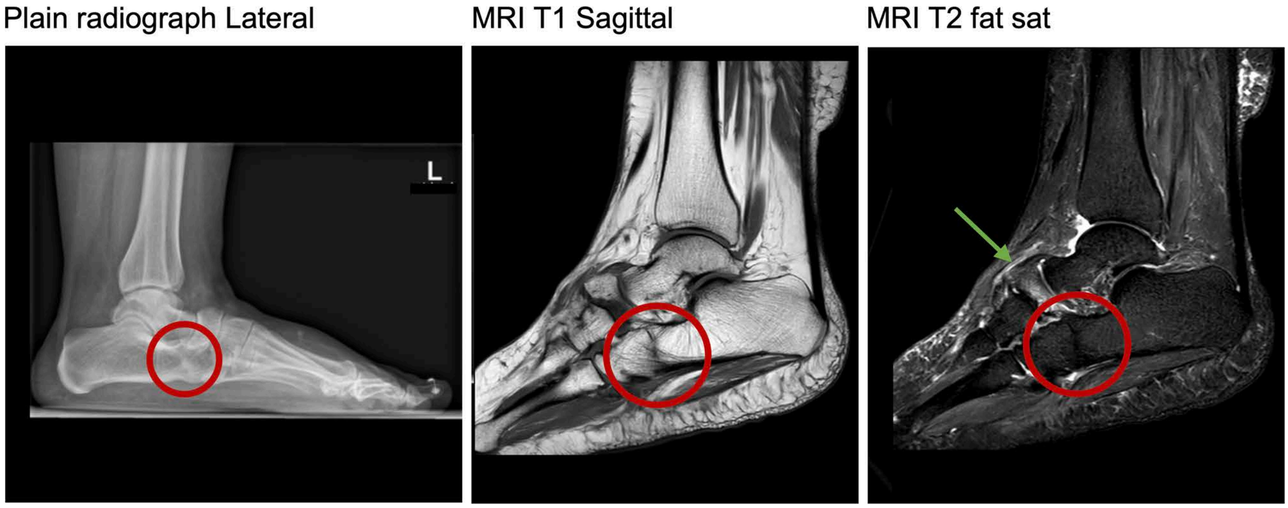


Same patient as Figs 5 and 7: Plain radiographs showed calcaneonavicular in the left foot with partial ossification (red circle). Planar scintigraphy of the left foot (lateral view) demonstrated increased blood pool (early phase) as well as bone-turnover (late phase) in the lateral left articulation between mid- and hindfoot and increased bone-turnover dorsally in the left ankle joint (blue arrow).

no bone edema at the site of complete osseous calcaneonavicular, but may reveal bone marrow edema in adjacent structures (Fig. 9, green arrow on T2 fat saturation, image on the right). Bone-SPECT/CT will typically show normal bone turnover at the complete osseous calcaneonavicular (Fig. 10a, lower images, green circle); however, with increased bone turnover (Fig. 10a; blue arrow) and slightly reactive blood pool (Fig. 10a; red arrow, upper image) in the navicular bone and the articulation of the navicular with the intermediate and the lateral cuneiform bone. This is consistent with secondary degeneration (with slightly reactive inflammation) at these two joints adjacent to the calcaneonavicular in flat foot deformity in the right foot.

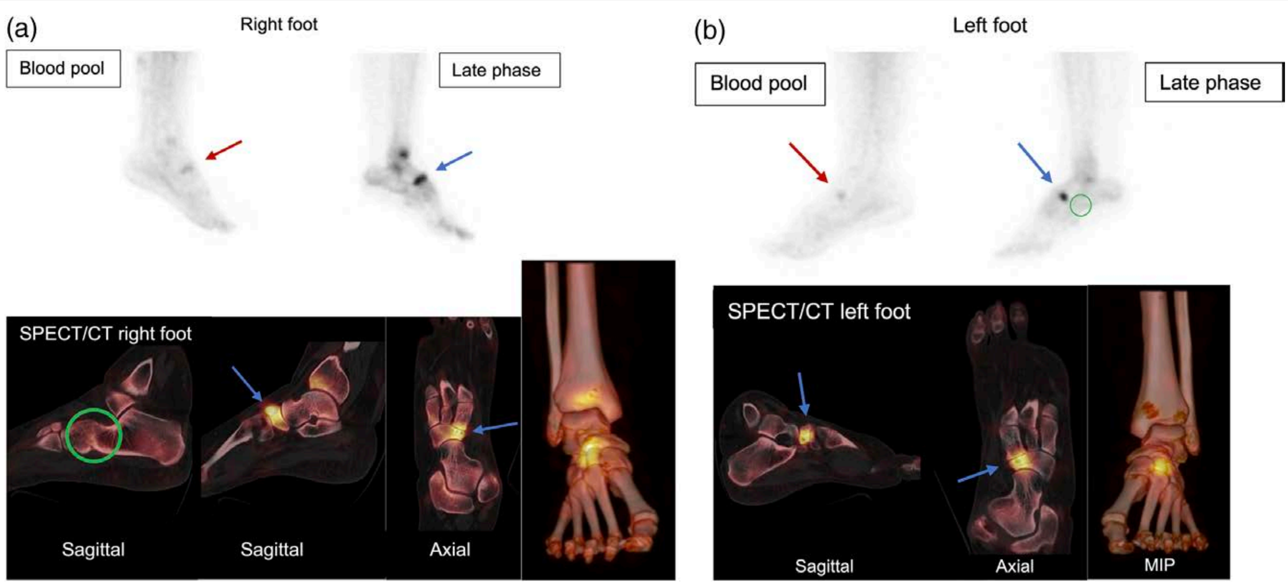
Next to increased bone turnover, also some increased blood pool may occur on bone-SPECT/CT as a sign of (reactive) inflammation (Fig. 10b: red arrow, upper image). Figure 10b also shows increased bone turnover (blue arrow) in the navicular bone and the articulation of the navicular with lateral cuneiform consistent with degeneration. Therefore, bone-SPECT/CT might reveal a combination of complete osseous calcaneonavicular and adjacent osteoarthritis, with the consequence management of a conservative approach for both findings. To conclude, bone-SPECT/CT is often used to pinpoint the causative adjacent structure (often a joint) of pain next to a complete osseous calcaneonavicular.

Fig. 9



Twenty-nine-year-old female patient, at the time of SPECT/CT with bilateral mid-foot pain and bilateral calcaneonavicular: Complete osseous calcaneonavicular on plain radiograph (left panel), with typical calcaneonavicular bone bar and flat foot deformity (pes planovalgus) on lateral projection (red circle). MRI (middle and right panel) with no bone edema at the site of complete osseous calcaneonavicular, but bone marrow edema in adjacent navicular bone (Fig. 9, green arrow on T2 fat saturation, right panel). CT, computed tomography.

Fig. 10

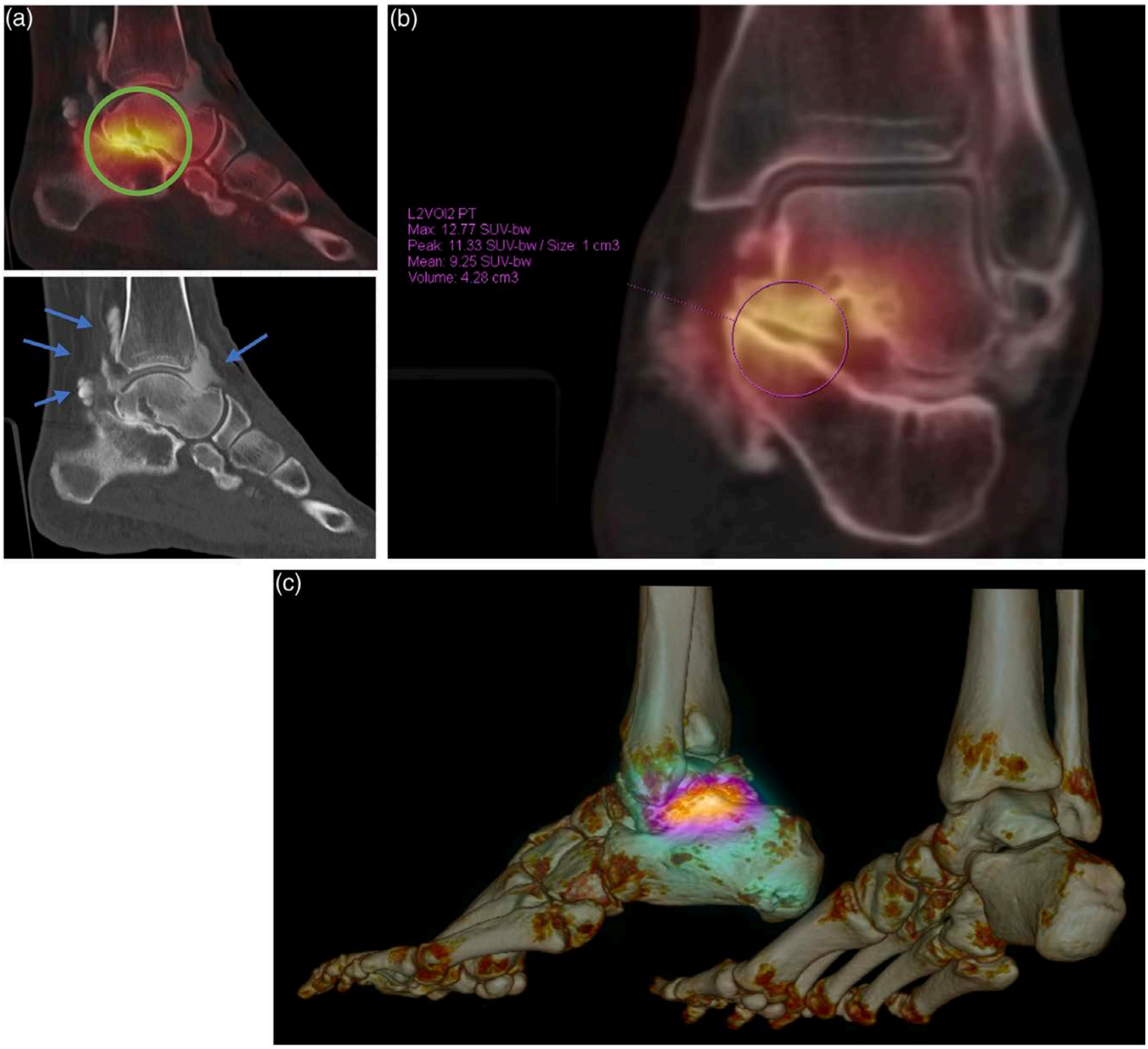


Same patient as Fig. 9 with bilateral calcaneonavicular. (a) Bone-SPECT/CT with normal bone turnover at the complete osseous calcaneonavicular (lower images, green circle, concerning the same patient as from plain radiographs and MRI (Fig. 9) with bilateral complete osseous calcaneonavicular, right foot is shown). Also note increased bone turnover (blue arrow) and slightly elevated blood pool (red arrow, upper image) in the navicular bone and the articulation of the navicular with the intermediate and the lateral cuneiform bone. This is consistent with secondary degeneration (with slightly reactive inflammation) at these two joints adjacent to the calcaneonavicular in flat foot deformity in the right foot. (b) Some increased blood pool on bone-SPECT/CT is a sign of (reactive) inflammation (red arrow, upper image). This panel also shows increased bone turnover (blue arrow) in the navicular bone and the articulation of the navicular with lateral cuneiform consistent with degeneration. CT, computed tomography.

Non-osseous talocalcaneal coalition

To optimally visualize the joint space and the structures immediately adjacent after plain radiographs, combining bone-SPECT/CT with arthrography (arthro-SPECT/CT) may be helpful (Fig. 11a). Additionally, the amount of increased bone-turnover can be measured semiquantitatively, either to assess severity or for intrapatient follow-up [22–24]. A small

Fig. 11



(a) Thirty-eight-year-old male patient presented with midfoot pain and plain radiographs were suggestive of TCC in the left foot (images not shown). Bone-SPECT/CT with intraarticular contrast medium shows non-osseous TCC of the posterior facet with increased bone turnover in the TCC; blue arrowheads pinpointing the intraarticular contrast medium, depicting a non-osseous TCC of the posterior facet with increased bone turnover in the TCC, in especially the talus (green circle). (b) Same patient as (a). Semiquantitative measurement of increased bone turnover in the non-osseous TCC on preoperative bone-SPECT/CT, with SUV_{max} of 12.8. (c) Same patient as (a and b). 3D reconstructions with maximal intensity projections (MIP) may be helpful to inform the clinician. CT, computed tomography; TCC, talocalcaneal coalition.

number of studies also evaluated quantitative bone-SPECT/CT parameters, such as SUV_{max}, in benign bone diseases other than tarsal coalitions, for example in osteoarthritis of the knee, and in epiphyseal growth plates [23,25]. In these studies, the SUV_{max} of quantitative bone-SPECT/CT was highly correlated with traditional imaging parameters for the severity of medial compartment osteoarthritis in the knee. Analogous to these findings, we incorporated quantification in bone-SPECT/CT in order to contribute to the limited evidence for the feasibility and usefulness of this technique in tarsal coalitions.

On preoperative bone-SPECT/CT if dedicated reconstruction algorithms are available (Fig. 11b) and subsequently to objectify comparison to post-surgery. Semiquantitatively, the change of the maximum standardized uptake value (SUV_{max}) at the site of the coalition increased from an initial value of 12.8 to SUV_{max} 20.8 (Fig. 11b; postoperative SUV measurement not shown).

Three-dimension reconstructions with maximum intensity projections may be helpful to inform the clinician (Fig. 11c).

Partly ossified talocalcaneal coalition

As already demonstrated in Fig. 2, lateral plain radiographs demonstrating a C-sign (blue arrows) are suggestive of TCC. Subsequent bone-SPECT/CT images in Fig. 2 show partially fused TCC (posterior facet) with increased uptake in the non-fused area, indicating the likely pain generator region. Bone-SPECT/CT adequately combines the ability to anatomically depict a partly ossified TCC as well as localizing the increased bone turnover, thus pinpointing the site of pain generation at the non-fused area in a patient with partially ossified TCC. For clinical management, this means that the patient could benefit from surgery in order to become pain-free.

Completely ossified talocalcaneal coalition

Also in this entity, the first indication of completely ossified TCC will consist of the C-sign on plain radiographs, no bone edema on MRI as well as the normal bone turnover on bone-SPECT/CT at the site of a completely ossified TCC. Also in these cases, MRI might especially detect soft tissue changes and bone-SPECT/CT is able to confidently exclude pain generation from the completely ossified TCC and to either exclude or pinpoint other (especially osseous) causes of pain.

Characteristic findings of imaging techniques in relation to the type of tarsal coalition, based on a combination of literature and our experience, are shown in Tables 1 and 2.

Imaging findings before and after treatment including metal *in situ*

Postoperative foot pain is a frequent clinical challenge, with often multifactorial etiology as the foot and ankle exhibit complex anatomy and function, and therefore difficulties in finding the pain generator are common [15].

In a non-operated patient, with no prior anatomical changes and no metallic osteosynthesis material, plain radiographs combined with MRI will often be successful with the considerations and limitations above. Bone-SPECT/CT is not only very helpful in primary surgical planning, but also has favorable characteristics in the

Table 1 Calcaneonavicular coalitions, characteristic findings per modality

	Non-osseous	Partly ossified	Completely ossified
Planar scintigraphy	Focal activity (early and late) in the lateral aspect of the articulation between hind- and midfoot	Focal activity (early and late) in the lateral aspect of the articulation between hind- and midfoot	No abnormal activity at the ossified tarsal coalition site, but increased focal activity (also in the blood pool) in the surrounding structures (navicular bone and naviculocuneiform joints)
SPECT/CT	Focally increased bone turnover at narrowed joint space, Anteater Nose sign, surface irregularity, subchondral cysts. Rest of foot unremarkable. No synchronous pathology	Better at delineating ossified fragments, but not for the soft tissue. Rest of foot unremarkable. No synchronous pathology	No abnormal activity at the ossified tarsal coalition site. Precise localization of the naviculocuneiform joints activity and osteoarthritis (sites of pain)
MRI	Optimal soft tissue characterization	Generalized edema in the area	No bone edema at the site of osseous tarsal coalition, but may reveal surrounding marrow edema
Plain radiograph	Anteater nose sign, low sensitivity	Anteater nose sign, low sensitivity	Osseous calcaneonavicular tarsal coalition visualized

CT, computed tomography.

Table 2 Talocalcaneal coalitions, characteristic findings per modality

	Non-osseous	Partly ossified	Completely ossified
Planar scintigraphy	Focal activity (early and late) in the lateral aspect of the hindfoot	Focal activity (early and late) in the lateral aspect of the hindfoot	No abnormal activity at the ossified tarsal coalition site, but increased focal activity can be seen in the surrounding structures (joints)
SPECT/CT	Focal activity (early and late) at narrowed joint space. Arthro-SPECT/CT may help in the evaluation of joint space and cartilage. Semiquantitative estimation with SUV_{max} is possible. Rest of the foot unremarkable. No synchronous pathology.	Shows partially fused talocalcaneal coalitions with increased activity in the non-fused area (site of pain generation). Rest of foot unremarkable. No synchronous pathology.	No abnormal activity at the ossified tarsal coalition site. Precise localization of the radiotracer activity and secondary osteoarthritis in the adjacent joints (site of pain generation).
MRI	Optimal soft tissue characterization	Generalized edema in the area	No bone edema. Useful to detect surrounding soft tissue abnormality
Plain radiograph	Low sensitivity, talar beaking	C-sign on lateral view	C-sign on lateral view

CT, computed tomography.

follow-up of patients after surgery, with SPECT not being affected by metallic implant artifacts. In patients with tarsal coalition, therefore, preoperative bone-SPECT/CT might be considered for both primary surgical planning as well as for follow-up.

Still, a major limitation of bone-SPECT to assess post-surgery bone is nonspecific tracer uptake at the site of surgery secondary to physiological remodeling [26]. The amount of this physiological bone reaction causing increased radionuclide uptake varies per exact type of surgery as well as the anatomical site within the foot and ankle. After arthrodesis in the hindfoot, the complete osseous union is achieved on average in 3.5–4 months in the subtalar joint, 6 months in the ankle joint, and up to 7.5 months after triple arthrodesis [15,27].

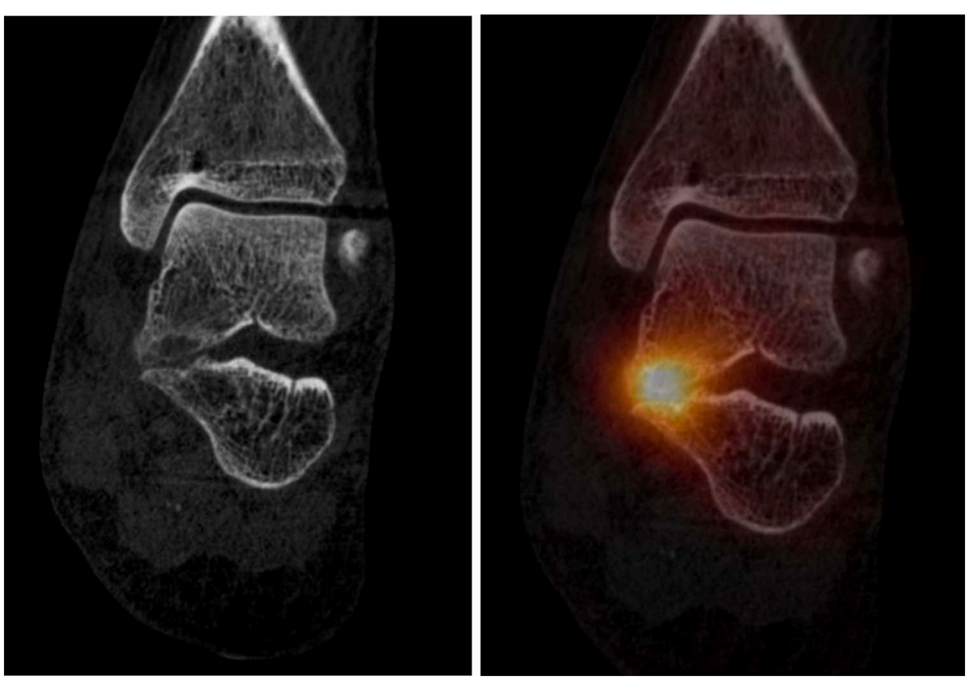
Preoperative bone-SPECT/CT may clearly pinpoint increased bone turnover in a tarsal coalition, to support ascertaining the indication for surgery. In patients that underwent surgery, including metallic implants, postoperative MRI will often not be performed because of hampered adequate visualization of the joints and relevant surrounding tissues as a result of metal hardware susceptibility artifacts. Bone-SPECT on the other hand is much less hampered and will usually be able to precisely pinpoint the location of the possible pain generator. The quality of CT can be impaired by hardware-induced artifacts, which might be (partly) overcome using metal artifact reduction (Please see Table 3) [28]. Bone-SPECT/CT performance before and after arthrodesis is illustrated by a 35-year-old patient with non-osseous TCC (middle facet). Preoperative images show increased bone turnover at an irregular narrow joint space and subchondral cysts in both talus and calcaneus and no degenerative foci elsewhere in the foot or ankle (Fig. 12). The same patient was later treated with arthrodesis of the left subtalar joint because of TCC; however, the patient continued to experience pain complaints. In this case, plain radiographs showed arthrodesis of the non-osseous TCC, without pinpointing the possible pain

Table 3 Parameters and settings of the two used SPECT/computed tomography systems for acquisition

	Philips BrightView XCT	Siemens Symbia Intevo bold
SPECT	64 views 20 s per view	60 views, 15 s per view
SPECT matrix	128 × 128	256 × 256
CT slice thickness	0.33 mm	0.75 mm
CT basic parameters	120 kV, 30 mA	110 kV, 120 mAs dose modulation
CT exposure time	7.2 s	13.4 s
CT pitch	N/A	0.9
CT matrix	512 × 512	512 × 512
CT reconstruction increment		0.5 mm

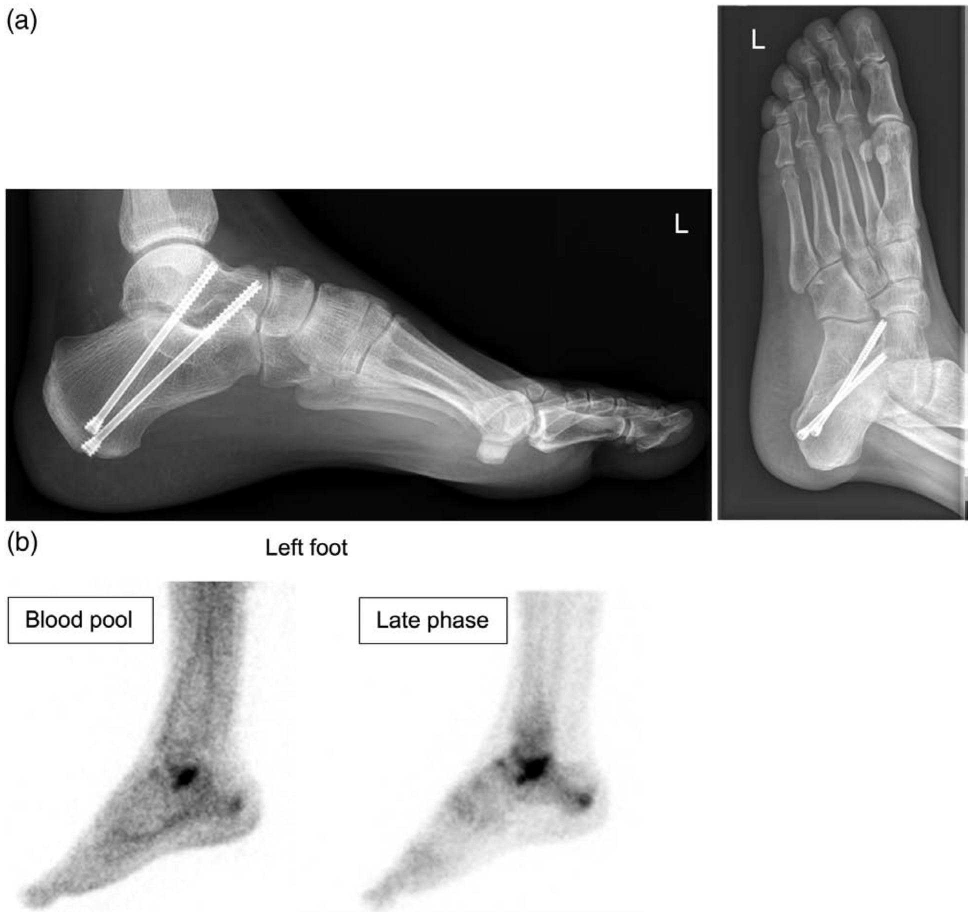
CT, computed tomography.

Fig. 12



Same patient as Fig. 11. Preoperative bone-SPECT/CT showed clearly increased bone turnover in a non-osseous TCC (middle facet), on accompanying low-dose CT an irregular narrow joint space and subchondral cysts in both talus and calcaneus. No degenerative foci elsewhere in the foot or ankle. CT, computed tomography; TCC, talocalcaneal coalition.

Fig. 13



(a) The same patient as from Fig. 12 was later treated with arthrodesis of the left subtalar joint because of TCC; however, the patient continued to experience pain complaints. Postoperative plain radiographs showed arthrodesis of the left non-osseous TCC, without pinpointing the possible pain generator. (b) Postoperative planar scintigraphy shows increased blood pool and bone turnover in the region of the left talocalcaneal articulation, which may indicate, but is non-specific for persisting TCC. TCC, talocalcaneal coalition.

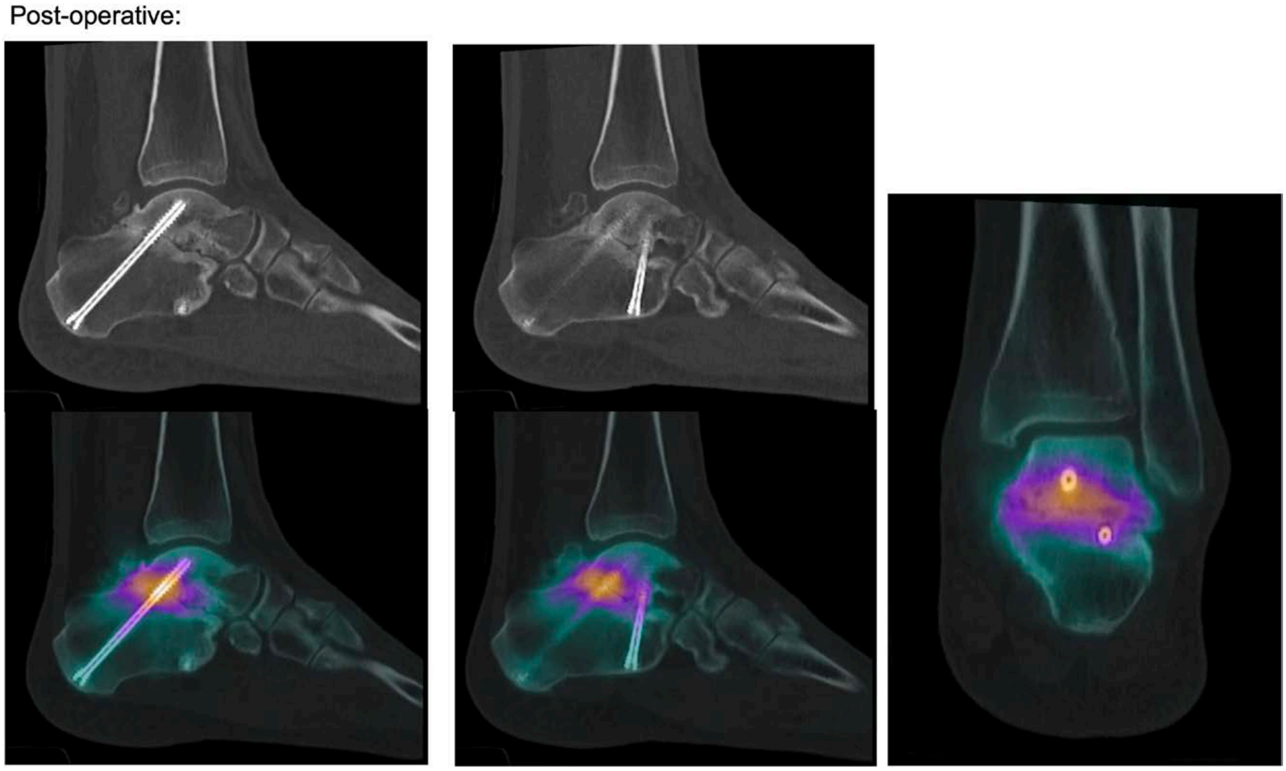
generator (Fig. 13a), as postoperative plain radiographs are often unable to pinpoint a specific pain generator after arthrodesis other than broken material, severe malalignments, or new fractures. Postoperative planar scintigraphy showed increased blood pool and bone turnover in the region of the left talocalcaneal articulation, which may indicate, but is non-specific for persisting TCC (Fig. 13b).

After arthrodesis of the subtalar joint because of a TCC, bone remodeling should slowly normalize in the fused joint and in the trajectory of the screw(s). The exact time of normalization of bone remodeling after arthrodesis in the foot is, as far as we are aware, unknown. In our experience; however, and also somewhat analogous to other osteosynthesis materials such as hip- and knee prosthesis and spinal fusion are expected to be approximately in the range of 1 and 1.5 years [29–31]. In the aforementioned case; however, pain complaints persisted 2 years after arthrodesis for TCC, and performed bone-SPECT/CT revealed continued increased bone turnover in the fused joint space without bony bridging at the site of the arthrodesis is consistent with delayed or non-union after arthrodesis (Fig. 14).

The change in uptake can be objectified semi-quantitatively by measuring the SUV in multiple time frames, in case visual assessment alone should remain indiscriminate (Fig. 15) but its scan-scan reproducibility should be taken into account when interpreting this change in SUV. The example shows semiquantitatively that the SUV_{max} at the site of the coalition increased from an initial value of 12.8 (Fig. 11b) to SUV_{max} 22.0 (Fig. 15). Thus, the combination of quantitative preoperative and postoperative bone-SPECT/CT, was able to detect persistent pathological bone-turnover at the site of the tarsal coalition before and after, reflecting the change in disease activity that often reflects the patient's reason of discomfort.

In another scenario, co-existing or newly developed pathologies (at other sites) can be sensitively detected,

Fig. 14



Same patient as Figs 12 and 13. Two years after arthrodesis of the subtalar joint because of a talocalcaneal coalition, bone-SPECT/CT was performed because of persistent pain complaints. Continued increased bone turnover in especially the posterior facet and irregular persistent joint space without bony bridging at the site of the arthrodesis, laterally from the initial TCC. This is consistent with delayed or non-union after arthrodesis (with no signs of failed material). CT, computed tomography; TCC, talocalcaneal coalition.

Fig. 15

Same patient as Figs 12–14. The amount of uptake can be objectified semiquantitatively by measuring the standardized uptake value (SUV), in case visual assessment alone should remain indiscriminate. Semiquantitatively, the SUV_{max} at the site of the coalition increased from the initial value of 12.8 (Fig. 11b) to SUV_{max} 22.0.

such as (secondary) osteoarthritis [25,28]. Figure 16 (coronal reconstructions shown), comparing preoperative and postoperative bone-SPECT/CT scans of a male patient of 41 years at first imaging, exemplifies this development with uptake in the TCC actually having decreased considerably (red circle) 2 years after arthrodesis, but a new focus of increased bone turnover at the site of arthrodesis laterally from the TCC has emerged (blue circle), developing new pain complaints. Therefore, in the follow-up of tarsal coalitions, especially with arthrodesis material *in situ*, bone-SPECT/CT may be useful in pinpointing clinically relevant changes in bone turnover in the tarsal coalition or elsewhere in the foot or ankle.

Technical considerations

The illustrative cases shown in this review comply with the recommendations below, performed on two different bone-SPECT/CT systems, the Philips BrightView XCT, Philips, Best, The Netherlands and the Siemens Symbia Intevo system, Siemens, Erlangen, Germany.

Acquisition

Acquisition of images is advised to accord to the current European Association of Nuclear Medicine practice guidelines for bone scintigraphy [16], combined with additional tailored acquisition details specifically for the foot and ankle as described by Kampen *et al.* [15]. This means that slice thickness should not exceed 1–1.5 mm and multiplanar reconstruction of the CT images, which may be helpful to get better images and clarity along with proper envisioning of the smaller joints. Injected activity should be reduced in children according to the latest standards adjusted to body weight [32]. Acquisition of the early 'blood pool' images started between 2 and 10 min post-injection with an acquisition time of 2–5 min for planar images to image co-existing tendinopathy or other inflammatory pathology in soft tissues or the bone [33].

Delayed 'mineralization' images were acquired 3–4 h post-injection including bone-SPECT/CT with low-dose CT for all patients, with the settings as follows:

The effective dose from the radiotracer administered for bone scintigraphy for an adult is approximately 3.0–4.0 mSv, whereas that in children is around 2.5 mSv [15]. Both feet can be imaged in the same session after a single injection of the radiopharmaceutical with no extra radiation burden when compared to imaging one foot and also at no extra time spent for the patient or the department. The amount of radiation burden for the CT part of the study is very low for the distal lower extremities, leading to an additional effective dose of less than 0.1 mSv [16]. For standardized positioning and avoiding motion artifacts, an immobilization device is advised in order to position the feet and the ankles appropriately. This dedicated foot support should consist of synthetic materials that do not introduce artifacts on the CT and should both immobilize with the upper ankle joint in a 90-degree position and be comfortable enough to stimulate immobilization.

Quantification of bone-SPECT/computed tomography

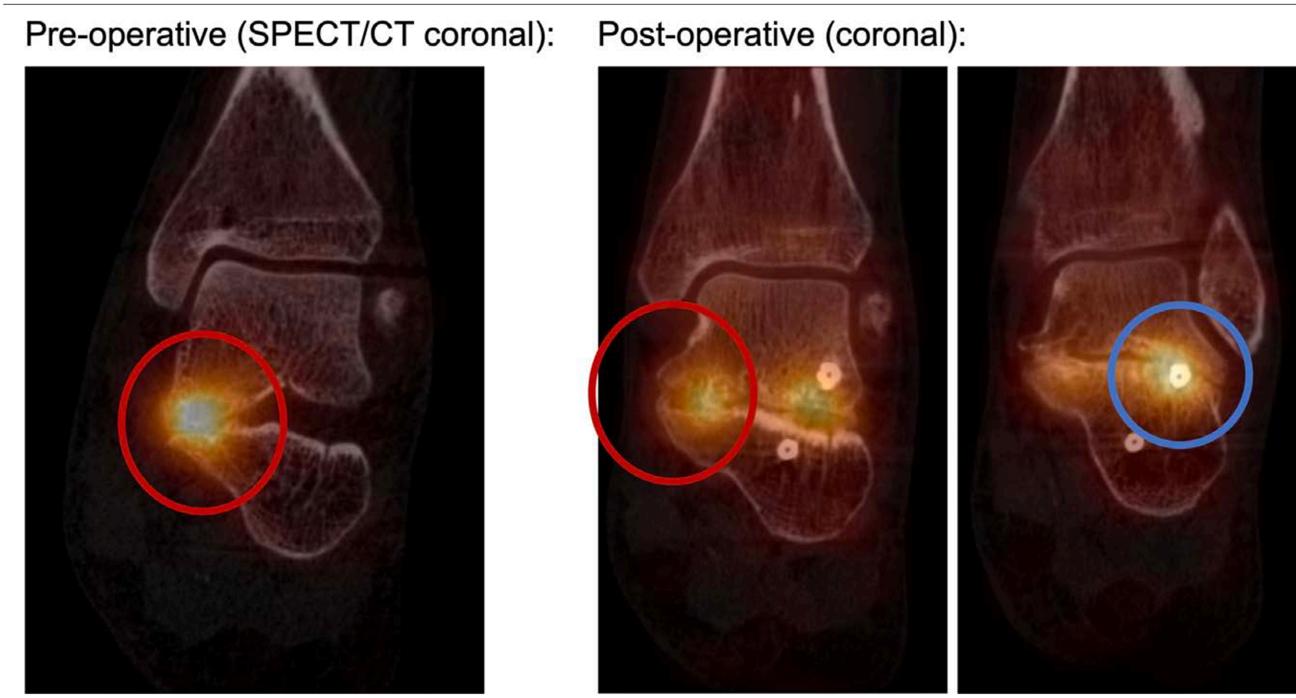
On the Siemens Symbia Intevo system, we performed quantification in addition to visual interpretation in patients with scans pre- and post-therapy, as only visual evaluation is often inconsistent in objectifying change in the disease activity [34].

Different techniques exist to reconstruct bone-SPECT/CT images to be used for quantification and specific Bayesian methods may outperform the more often used OSEM reconstructions with improved quantitative accuracy [35]. Both research and clinical practice on quantitative bone-SPECT/CT have worldwide gained the most experience with the analysis of bone metastases in prostate (and to lesser extent breast) cancer [36].

Suggested diagnostic algorithm

As tarsal coalitions are a congenital condition and presentation is usually in the adolescent age and mostly at

Fig. 16



Male patient of 41 years at first bone-SPECT/CT. When comparing preoperative and postoperative bone-SPECT/CT scans (coronal reconstructions shown), the uptake in the TCC has increased considerably (from previous, but a new focus of increased bone turnover has developed at the site of arthrodesis laterally from the TCC (blue circle). CT, computed tomography; TCC, talocalcaneal coalition.

an age younger than 50 years old, imaging with the least amount of ionizing radiation is preferred. We suggest the diagnostic algorithm shown in Fig. 17 for optimal diagnosis in patients with the (suspected) tarsal coalition or unexplained tarsal pain at both primary diagnosis and (postsurgical) follow-up (Fig. 17).

Discussion and recommendations

Although the non-exhaustive list of indications in the European Association of Nuclear Medicine (EANM) guidelines does not specifically mention tarsal coalitions, bone-SPECT/CT is an adequate imaging modality to accurately depict different types of tarsal coalitions as an adjunct to plain radiograph imaging. In primary diagnosis, it increases diagnostic value especially TCC, as these can be challenging to be revealed using plain radiography. Bone-SPECT/CT also shows additional (secondary) osteoarthritis or other accompanying synchronous pathology in the foot or ankle, and is able to exclude accompanying bone pathology with high readers confidence. Planar blood pool images may aid in the diagnosis of tarsal coalition typically depicting focally increased radionuclide uptake.

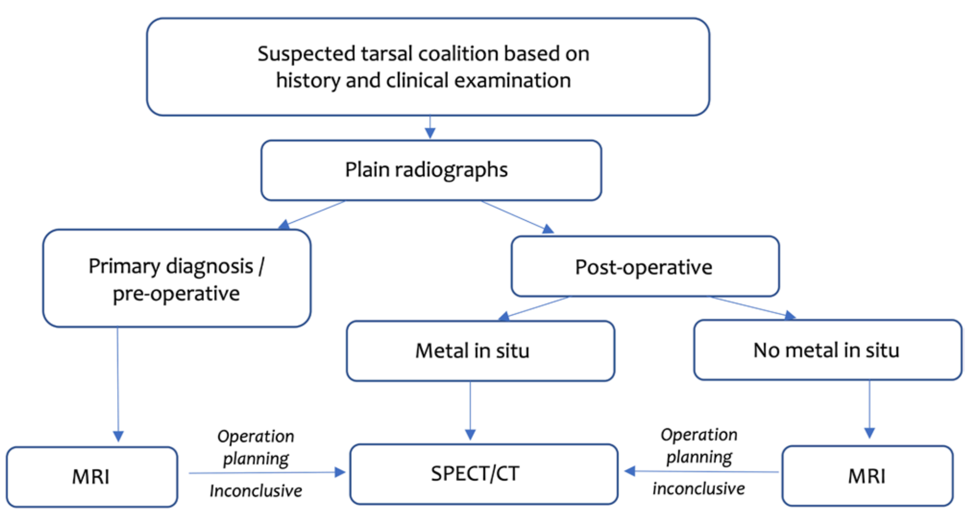
Additionally, blood pool bone-SPECT/CT has recently been described as a proof of concept [37], but evidence for clinically added value for using blood pool bone-SPECT/CT images for tarsal coalitions is non-existent until now, as far as we know.

Quantification in bone-SPECT/CT may add objectivity and certainty in primary diagnosis, and could especially be of value in follow-up situations to depict change more objectively, in our experience. The accuracy of bone-SPECT/CT quantification does depend on many factors: the use of a collimator, the detector trajectory, the need for more complicated correction for scatter and attenuation than in PET, and reconstruction algorithms [38]. Corrections for photon attenuation and scatter, collimator modeling, and reconstruction, have improved reconstruction, thus enabling absolute SPECT quantification [38]. However, the evidence for the added clinical value of quantitative bone-SPECT/CT over visual assessment in both primary diagnosis and in the follow-up of benign diseases is still very limited, and more research is needed to precisely correlate (changes) in measured SUV_{max} to (change in) clinical findings [22,25,28].

Conclusion

This illustrated review demonstrates added clinically useful information of bone-SPECT/CT over plain radiographs and MRI in suspected tarsal coalitions (both calcaneonavicular and TCC). MRI is known to be especially advantageous in depicting the soft tissues, whereas bone-SPECT/CT excels in the fast and accurate characterization of the bone pathology and confidently excluded any synchronous lesion elsewhere in the foot and ankle. Second, bone-SPECT/CT is being utilized by our orthopedic surgeons for surgery planning because of optimal insight into the structure of the bones and 3D localization of bone metabolism, and especially postoperatively bone-SPECT/CT pinpoints the culprit site from where the pain originates. Moreover, bone-SPECT/CT is of extra value in postoperative patients where MRI is either contra-indicated or considerably hampered to pinpoint the possible pain generator by depicting the bone turnover, especially in the presence of osteosynthesis material.

Fig. 17



Proposed diagnostic algorithm for optimal diagnosis in patients with the (suspected) tarsal coalition or unexplained tarsal pain at both primary diagnosis and (post-surgical) follow-up.

Acknowledgements

Conflicts of interest

There are no (potential) conflicts of interest for any of the authors.

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