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RESEARCH ARTICLE

Comparative role of scintigraphy in sporting injuries in the new millennium

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ABSTRACT

Exercise for good health and as a prerequisite for most sporting endeavours is both an aspirational and necessary requirement at a time when obesity plagues much of the well-developed world. It has led to great advances in the science of exercise and a medical specialty devoted to sporting injuries. Epidemiology of sporting injury is crucial in this process in order to prevent injury and to focus attention on dangerous practices in some sports. The bone scan was historically considered a mainstay for the diagnosis of sporting injuries involving stress fractures, acute fractures and some soft tissue injuries. However, the role of scintigraphy has been supplanted by magnetic resonance imaging (MRI) in many of these settings, largely due to its high contrast resolution for soft tissues, spatial resolution of the relevant anatomy and the absence of radiation exposure. Nevertheless, there remains a valuable contribution from scintigraphy with the development of single photon emission computed tomography (SPECT) co-located with x-ray computed tomography (CT) in the same instrument. The place of scintigraphy in the evaluation of sporting injuries needs to be critically evaluated against the competing modalities of CT, MRI and high-resolution ultrasound. It is no longer appropriate or critically acceptable to examine scintigraphy in isolation from the other available imaging modalities.

Keywords: Trauma, sport, anatomy, stress fracture, scintigraphy.

Introduction

Exercise is now considered a form of medicine for the prevention of ailments and as a prerequisite for participation in most sports. Participation in sport has increased, especially in childhood and has become a part of the school curriculum in most Western countries. Yet there is an increasing prevalence of obesity, underlining the importance of not only exercise but of correct dietary habits. The interest in sport has also stimulated an industry in the production of sporting goods, a rich and rewarding entertainment facet and a medical specialty devoted to sporting injuries. Epidemiology of sporting injury is therefore also crucial in this process as it allows a rational basis for imaging and the prevention of injury.

The bone scan was one of the mainstays of imaging sporting injuries over 30 years ago. The imaging landscape has progressed with improvements in technology that have led to the development of multiple rapid sequences in MRI, improvements in CT and high-resolution ultrasound. A high level of musculoskeletal specialization in these modalities has led to serious confusion in the choice of which modality is best for particular injuries. The advent of SPECT/CT imaging in scintigraphy has combined a high level of function with the exquisite spatial resolution of CT, transforming the specialty beyond the early days of high sensitivity and poor specificity. One therefore needs a rational evaluation of which modality provides the most accurate answer for the various sporting injuries. It is no longer appropriate to evaluate scintigraphy in isolation from the competing modalities without critical analysis and the development of an appropriate algorithm and framework to guide our colleagues in sports medicine and orthopaedic surgery in the best "bang for the buck".

Epidemiology of childhood sporting injuries:

There is increased participation of children (age < 15 years) in sport with reports of approximately 20 hours per week in in training for sports such as tennis[1]. That period of time carries an increased risk of injury. One study found that 65% of all sports-related injuries (Total 4.3M) presenting to the accident and emergency department were in patients under the age of 19 years[2].

The available data indicates that the vast majority of serious injuries are young males playing sports such as football, rugby and soccer and in older girls performing gymnastics.

Figure 1 shows a much higher rise in the rate of injuries after the age of 15 years for boys more than girls, with a decline in the rate of injury for girls after the age of 12 years. The rate of injury by sport would indicate a preponderance of injuries in boys playing ice hockey, rugby union and soccer. Injury rates for girls are highest in soccer, basketball and gymnastics.

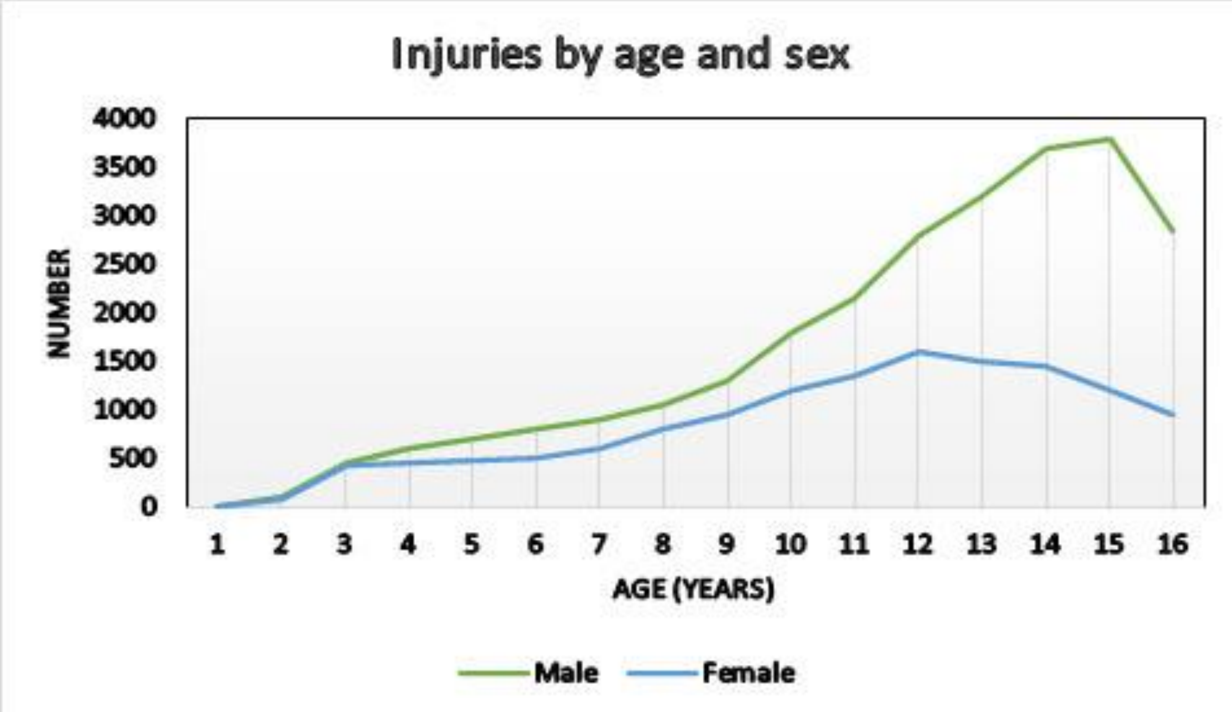

Figure 1. Injuries by age and sex. The graph demonstrates a progressive rise in the number of sporting injuries to the age of 12 years in females and to approximately 15 years in males with a subsequent drop-off after these ages.

Epidemiology of sporting injury in adults

The epidemiology of sporting injury in adults needs to be categorised into amateur and professional. The majority of injuries in amateurs are generated through playing contact sports such as football, rugby and soccer. The cost of these injuries has been estimated at approximately AUD$ 1 Billion (US$ 0.71 Billion, Euro 0.61 Billion) in a population of 25.5M. The injury rates are significantly higher between the ages of 18 and 30 years with 40% considered minor, 57% of moderate severity and 3% requiring hospitalisation. The highest rate was for soccer at 20.3/1000 hours of participation[3].

The highest injury rate in professional sport has been reported in American football (Gridiron), and in particular, the National Football League which outstrips the injury rate in rugby union.[4] It also has the highest incidence of traumatic brain injury in all the contact sports. The rate of injury by sport is shown in Figure 2[4]. The most common site of injury is to the knee, ankle, shoulder and head.

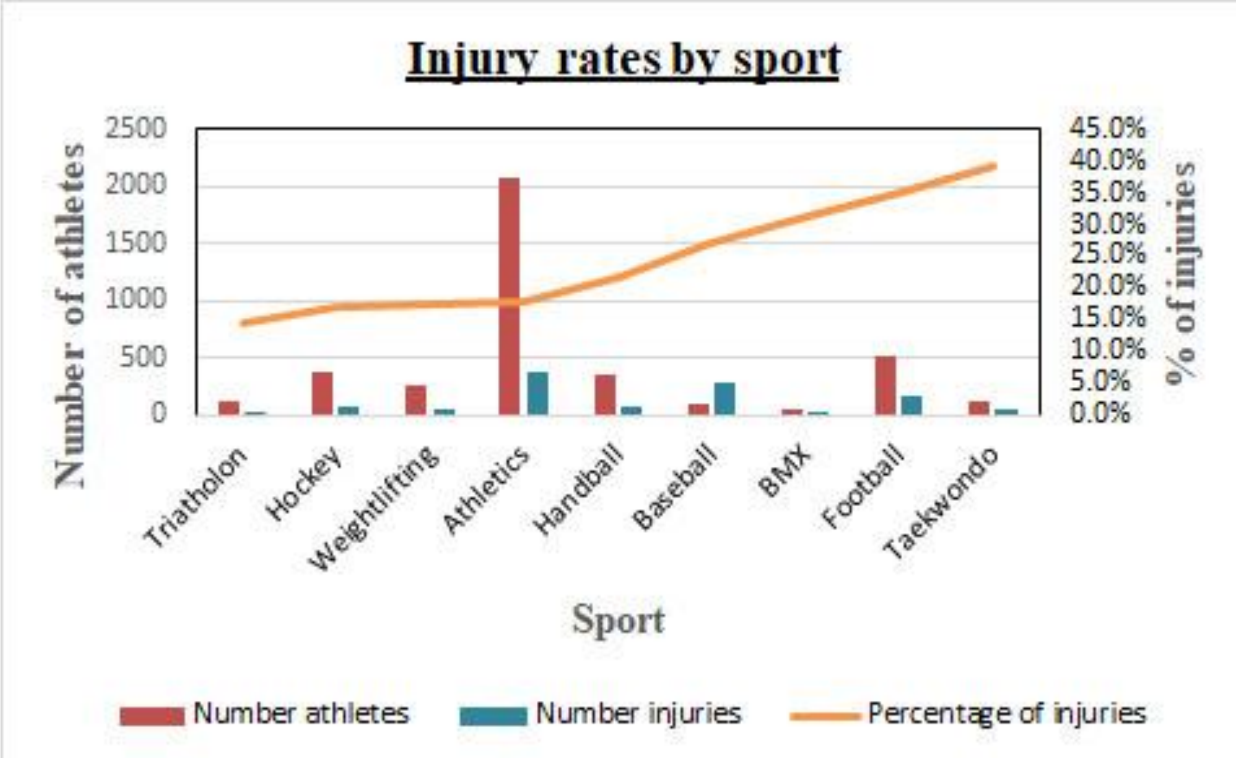

Figure 2. Injury rates by sport. The rate of injury is highest in the martial arts where it reaches almost 40% of participants. The rate of injury in triathlons is lowest with intermediate rates of injury in hockey, baseball and football.

Soccer injuries primarily affect the lower limbs (92%)[5], thigh (predominantly hamstring - 37%)[5] knee and ankle[3, 6, 7]. This pattern of injury has been ascribed to the increase in game intensity and the drive to simulate this in training[3, 7].

Females playing gender-comparable sports have a significantly higher rate of anterior cruciate ligament injury by a factor of 8 regardless of the level of contact in the sport[8]. Basketball, soccer and soft-ball were the main contributors to the injury. A similar finding was also made with ankle injuries where the rate of female injuries was significantly higher than in males (53% vs. 47%; $P < .05$)[9].

Overuse versus acute injury

Overuse injuries result from repetitive cumulative micro-trauma, fundamentally as there is little time for healing due to the frequency of training/ playing. Such injuries include tendinopathy, bursitis, medial tibial stress syndrome and stress fractures. The type of injury usually occurs in non-contact sports such as distance-running, rowing and swimming. In contrast, acute injuries occur in sports that require ballistic movement such as in soccer, basketball and high-contact sports such as rugby, martial arts and the National Football League.

In one study of athletic injuries by sport and sex, 573 injured collegiate athletes reporting 1317 injuries during a three-year period, over 50% reported more than one injury.[6] Approximately 30% were overuse injuries and 70% acute injuries. The majority of acute injuries were in males while female athletes reported a much higher proportion of overuse injuries. The principal site of both acute and overuse injuries was to the lower limbs.

Pathophysiology of sporting injuries

It is clear that most acute injuries occur from either direct or rotational force being applied to bone, tendon or muscle[2, 7]. This occurs in predominantly contact sports or where there is rapid change in direction in sports such as Gridiron, rugby union, basketball or netball, principally involving the knee or ankle[7]. These injuries may result in internal derangements of the cruciate ligaments, menisci or osteochondral elements of the knee or ankle in association with ligamentous injuries. The more complex pattern of injury is to the soft tissues and bones due to overuse. Overuse injuries are considered biomechanical events resulting from fatigue of biological tissues due to the magnitude of loading and frequency of repetition.[10] The concept is well illustrated in the work of Daffner and Pavlov[11] shown in Figure 3 indicating the progression to stress fracture. However, the unknown factor that is difficult to take into consideration during in vivo modelling is the effect of rest and healing between bouts of activity. The widespread clinical belief is that the frequency of the activity is a key factor in progression to injury, where biological tissues do not have the requisite time for healing and repair[11].

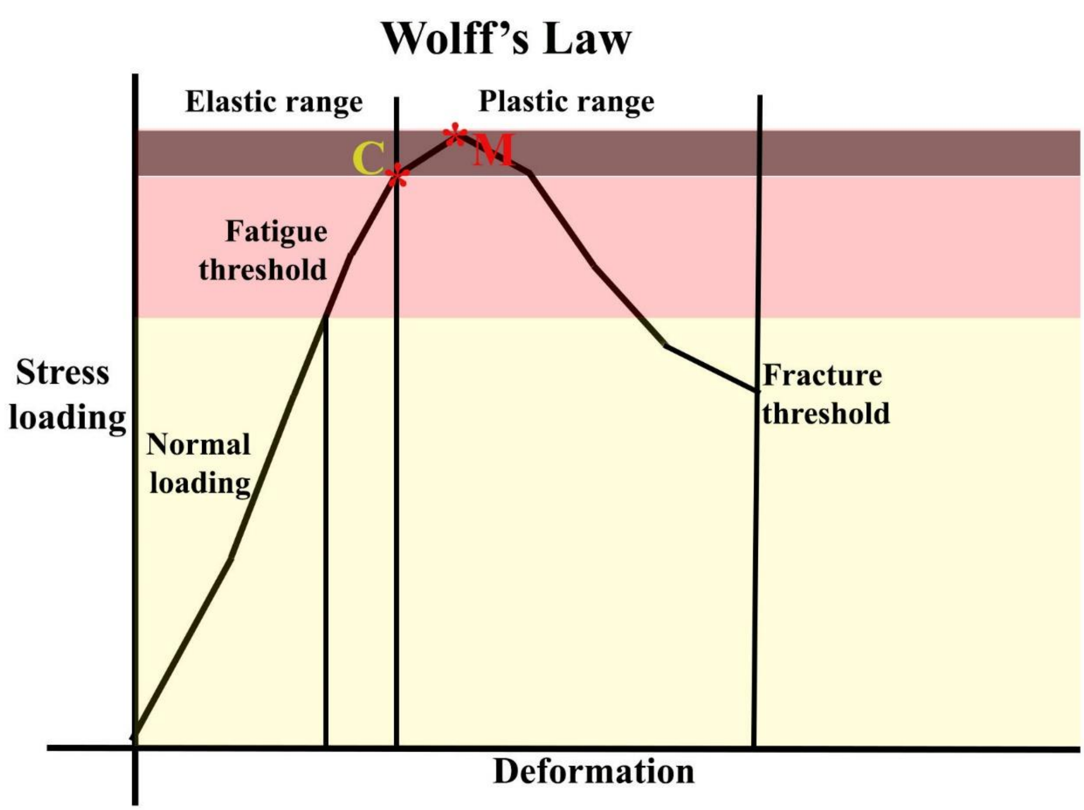

Figure 3. Graphic illustration of Wolff's law. As the rate of stress increases within the elastic range of normal bone, there is deformation with complete return to the resting state. If the elastic range is exceeded (C) there may be deformity and if M is exceeded microfractures occur. If fatigue continues then cortical fracture occur with permanent deformity.

Technical factors in scintigraphic imaging.

The most widely heard historical complaint about scintigraphic imaging has been of exquisite sensitivity but poor specificity.[12] It led to the widespread quotation of *Nuclear* medicine as *Unclear* medicine. However, the last 20 years has seen the widespread implementation of hybrid imaging devices consisting of both a gamma camera and co-located x-ray computed tomography (CT). This fundamentally allowed the fusion of single photon emission computed tomography (SPECT) with a CT scan to allow both anatomical and functional data in a single image, thereby significantly improving the specificity of the test. It could refashion the concept of nuclear medicine as *NewClear* Medicine! Furthermore, reconstruction methods have moved from filtered back projection to statistical variations such as ordered subset expected maximisation (OSEM)[13] and allowed the implementation of concepts such as resolution recovery to better improve the quality of the SPECT images. It achieves this by combining attenuation and scatter correction with mathematical modelling of the collimator and its distance from the patient (Figure 4)[14].

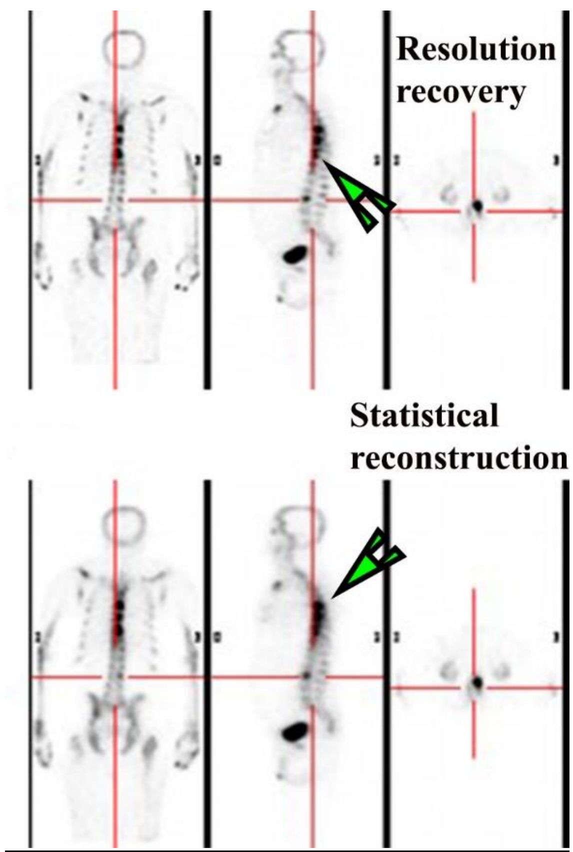

Figure 4. Resolution recovery. The two panels illustrate the importance of resolution recovery processing in improving the spatial resolution of the scintigraphic SPECT study due to the application of attenuation and scatter correction and modelling the geometry of the collimator. The difference with the application of only statistical methods of reconstruction without resolution recovery (arrowheads) is shown in the lower panel where there is a significant loss of spatial resolution. (Image courtesy of Mr. Maurice Trochei. General Electric, Sydney, Australia).

Scintigraphy in poly-trauma

One of the greatest advantages of scintigraphic imaging is the acquisition of a whole-body image in cases of suspected poly-trauma, especially in the unconscious patient. The technique could also allow more focused SPECT/CT imaging at sites of detected abnormalities. This was first canvassed in the early 1990s by Spitz et al in patients with poly-trauma after motor vehicle accidents[15]. It is particularly impressive after high-impact sporting injuries where consciousness may be affected and a clear history is difficult to obtain. Figure 5 shows such an example from a patient who had a high-speed bicycle crash with multiple injuries.

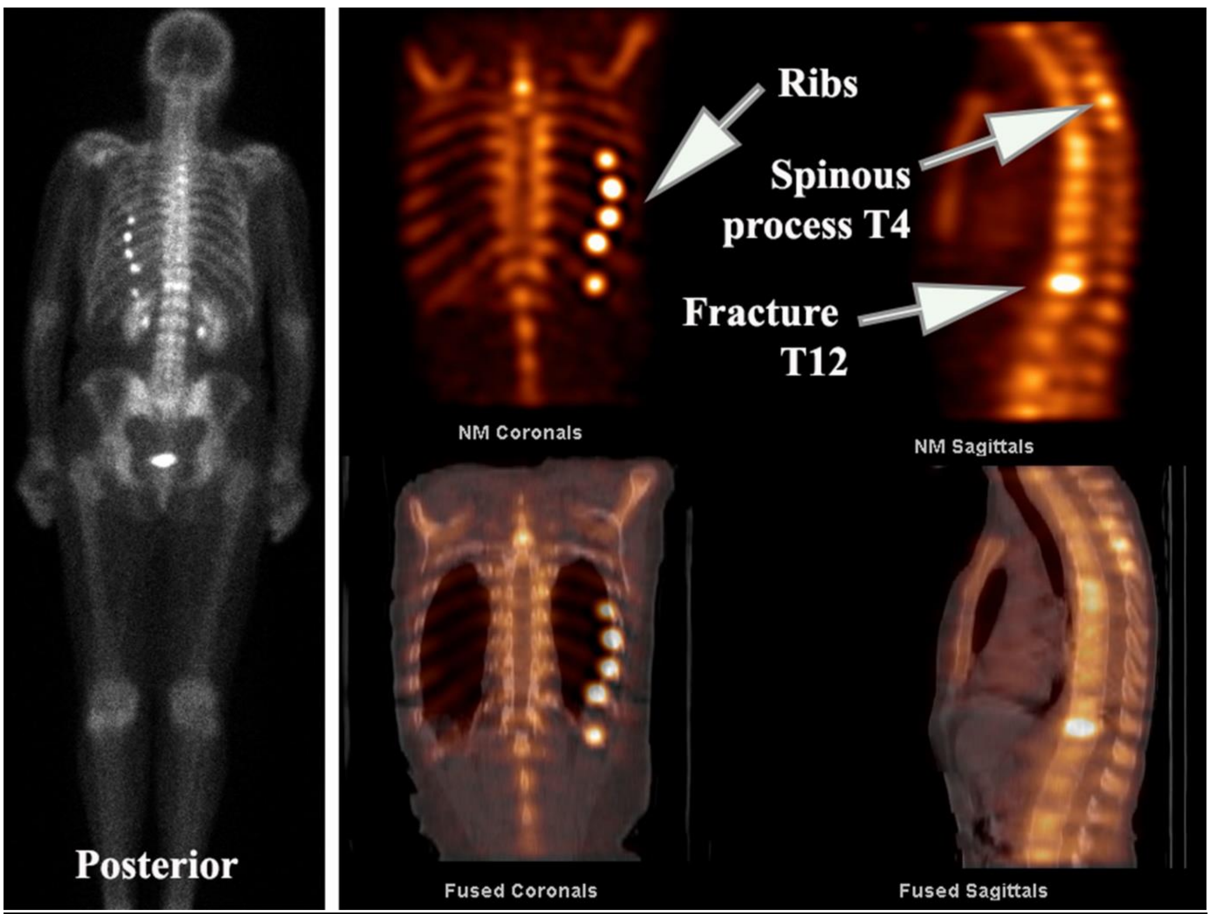

Figure 5. Poly-trauma. The patient presented after a high-speed collision and fall from a bicycle. There was increasing complaint of pain in the thoracic spine and left hemithorax where early plain films had shown no significant abnormality. The patient was referred for bone scintigraphy which demonstrated multiple rib fractures in the posterior aspect of the left hemithorax (arrows), intense uptake in the spinous process of T4 at a site of fracture and a compression fracture of the body of T12. These were unexpected findings.

Soft-tissue injuries

Soft-tissue injuries most often involve the tendon-muscle unit but may involve multiple other structures such as the fascia, bursae, joint capsules and neurovascular structures. The musculoskeletal system constitutes approximately 45% of total body weight, hence its commonality as a principal site of injury[16].

GROIN INJURIES

Groin injuries are common in athletes, accounting for approximately 5% of all sporting injuries[17] and pose a difficult diagnostic challenge which is highly reliant on imaging. The causes vary from inguinal hernias to osteitis pubis, adductor strains, iliopsoas bursitis, localised hip pathologies such as femero-acetabular hip impingement and stress fractures. The most common cause is adductor strains, particularly in sports such as soccer, accounting for 62% of all groin injuries, often in association with osteitis pubis.[18] A more complex injury to the dorsal interosseous ligament of the sacroiliac joint (Figure 6) can present with multiple tendon abnormalities around the pelvis that cause both ipsilateral buttock and groin pain, as shown in Figure 7.[19, 20]

SACROILIAC JOINT INCOMPETENCE

Mechanical dysfunction of the sacroiliac joint is more common than intervertebral disc disease as a cause of lateralising lower back pain[21]. It is characterised by a specific injury to the dorsal interosseous ligament in the posterior aspect of the upper sacroiliac joint (Figure 6) which follows trauma which may be either repetitive or by either a direct fall onto the buttocks or a twisting injury as occurs in gymnastics, rugby or soccer. The injury triggers a major loss of sequencing of the abdominopelvic muscles that force-close the pelvic ring and lead to compensatory neuromuscular changes with loss of closure of the pelvic ring. This leads to a painful failure of ground force transmission from the lower limbs to the spine. It is characterised by overactivity of the adductors, hamstrings, iliopsoas and gluteus medius muscles which manifest as enthesopathies and may be complicated by ipsilateral femero-acetabular hip impingement and osteitis pubis, as shown in Figure 7. SPECT/CT imaging of the standard bone scan is the defining modality for the diagnosis, where the principal abnormality is increased uptake of tracer in the injured dorsal interosseous ligament as shown in Figure 6[19]. MRI and CT scanning have shown no significant diagnostic abnormality in the condition. It is also associated with recurrent hamstring injuries, particularly in rugby and soccer[22]. The importance of diagnosis of the condition lies in the simplicity of the treatment, which is specialised physiotherapy, yielding a good therapeutic response in 80% of cases[19]. Imaging criteria for the diagnosis are shown in Figures 6 and 7.

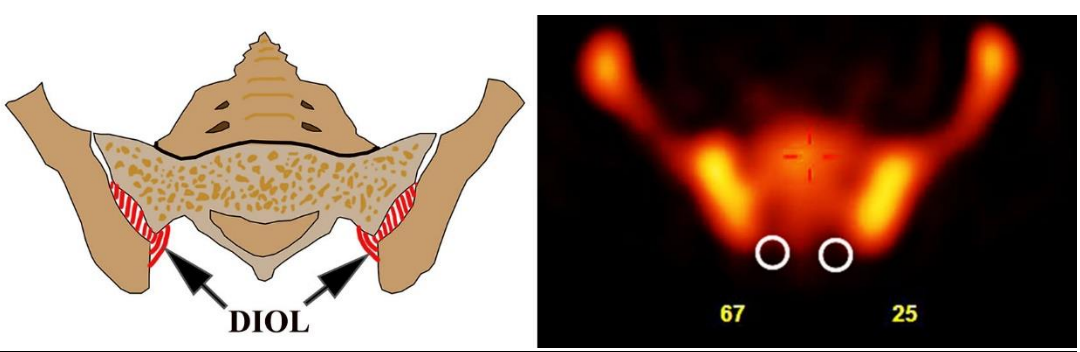

Figure 6. The principal abnormality of sacroiliac joint incompetence. The graphic in the left panel shows the site of the dorsal interosseous ligaments in the posterior aspect of the sacroiliac joints at approximately the S2 level (arrows). The right panel shows the count profiles of soft-tissue uptake in the ligaments in the transaxial projection of the SPECT study, which is significantly higher on the injured right side.

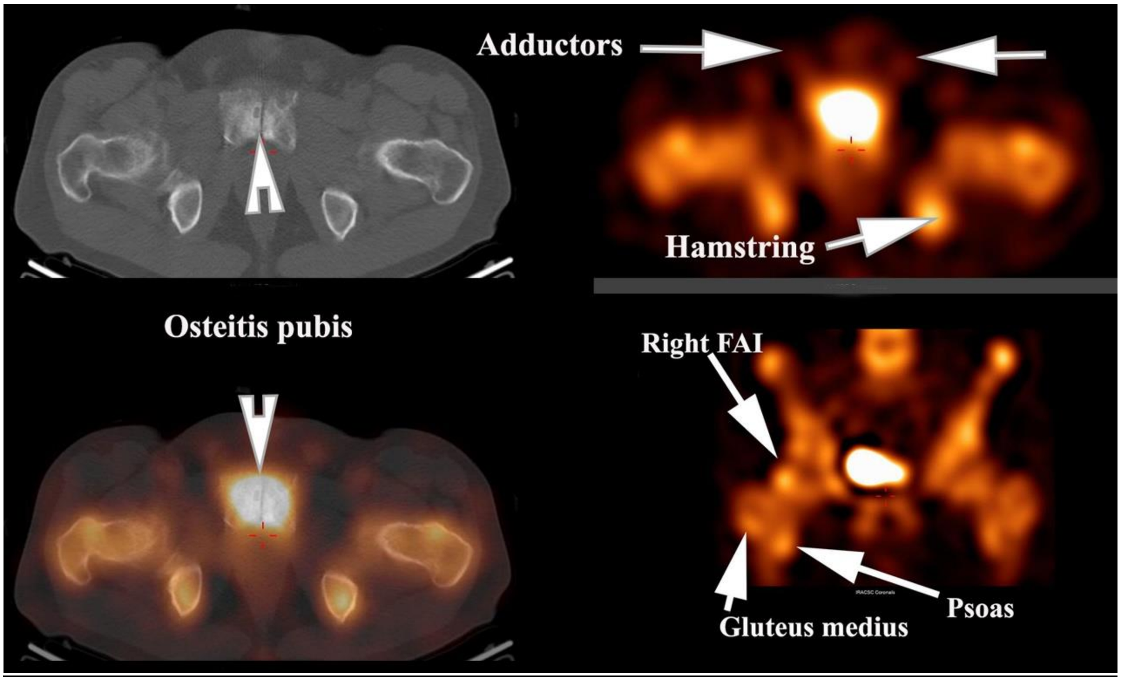

Figure 7. Scintigraphic features of sacroiliac joint incompetence. The female patient presented with right lower back pain following a heavy fall onto the right buttock at netball. The source of pain was not clinically or radiologically evident and she was referred for bone scintigraphy with SPECT/CT imaging. The SPECT/CT study shows evidence of osteitis pubis (arrowhead), enthesopathies (arrows) of the adductor tendons around the pubic synthesis, left hamstring, right gluteus medius and right psoas tendon insertions. There is also evidence of right femero-acetabular hip impingement (FAI). These are the principal abnormalities that reflect the altered sequencing of the abdominal and pelvic muscles following injury to the dorsal interosseous ligament in the posterior aspect of the sacroiliac joint.

COMPLEX REGIONAL PAIN SYNDROME (CRPS)

CRPS remains an enduring problem with both diagnosis and therapy. It is a pain syndrome that is characterised by burning pain, swelling, hyperaesthesia, hyperhidrosis and trophic changes in the skin and bone in the distribution of the symptoms. Approximately 90% of cases are associated with trauma and the remainder have no identifiable trigger[23]. The aetiology remains the subject of much conjecture but the principal hypothesis is of injury to the sympathetic or sensory nerves with a significant inflammatory component leading to changes in blood flow in the affected area[24]. Sympathetic nerve blocks measurably alter the pattern of blood flow and parallel the clinical response to treatment on triple-phase bone scanning[24]. Therapy of the syndrome is complicated and the results are variable, as most cases resolve within 6 months[23] with a small proportion requiring rehabilitation, physical therapy, nerve blocks or pharmacological therapeutics. The diagnosis is based on clinical findings and may be confirmed in difficult cases with triple-phase bone scanning or MRI. The principal pattern on the bone scan is of intense hyperemia in the dynamic and blood-pool phase with increased periarticular uptake in the delayed image. These changes are illustrated in Figure 8 with the MRI changes of associated bone marrow oedema shown in Figure 9.

The condition may cause alarm in children where the scintigraphic manifestation may be of a marked reduction in blood flow to the affected area, raising the spectre of a vascular catastrophe. The condition is more common in females and more frequent in the lower limbs with a significant psycho-social component[25].

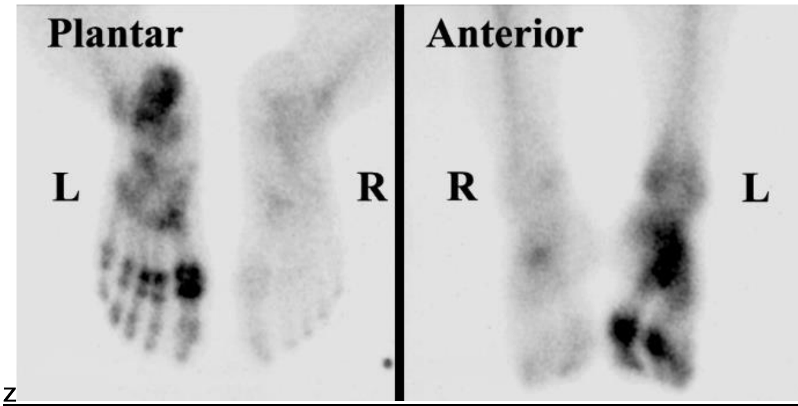

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Figure 8. Complex regional pain syndrome (CRPS). The planar images demonstrate intense periarticular uptake in virtually all joints in the left foot without a focal abnormality in uptake. This is the typical pattern that reflects the neurovascular alteration in blood flow to the left foot following a minor injury which the patient could not recall but with significant pain, swelling and alteration in colour of the left foot due to vasodilation and altered sensation.

Figure 9. Complex regional pain syndrome (CRPS). MRI appearance in a patient with CRPS where there is diffuse bone marrow and soft-tissue oedema in the affected limb.

MUSCLE INJURY

The scintigraphic detection of muscle injury is well known and was reported as far back as 1983 in 90% of ultra-marathon runners[26]. These initial reports were in patients with rhabdomyolysis and significant elevations of creatine phosphokinase. The condition has also been reported in weightlifting,[27] where there is clear delineation of uptake in the muscles involved by rhabdomyolysis, as shown in Figure 10. The aetiology of uptake is most likely related to muscle necrosis, similar to the pathophysiology of myocardial uptake of the bone scanning agents after infarction. A similar pattern of uptake also occurs with direct bruising of muscle and subsequent calcification which is apparent on bone scintigraphy with SPECT/CT (Figure 11).

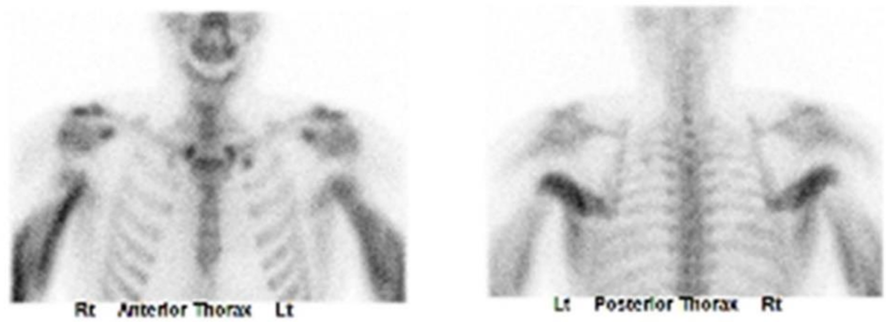


Figure 10. Rhabdomyolysis. Intense symmetrical uptake of tracer is apparent in the muscles of the shoulder girdle and arms following an intense accelerated and unsupervised weightlifting program in a teenager. It reflects the resultant extensive muscle necrosis.

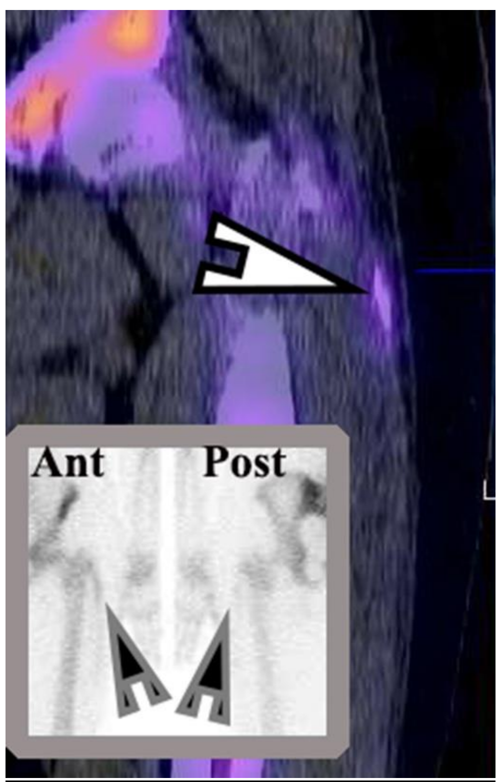
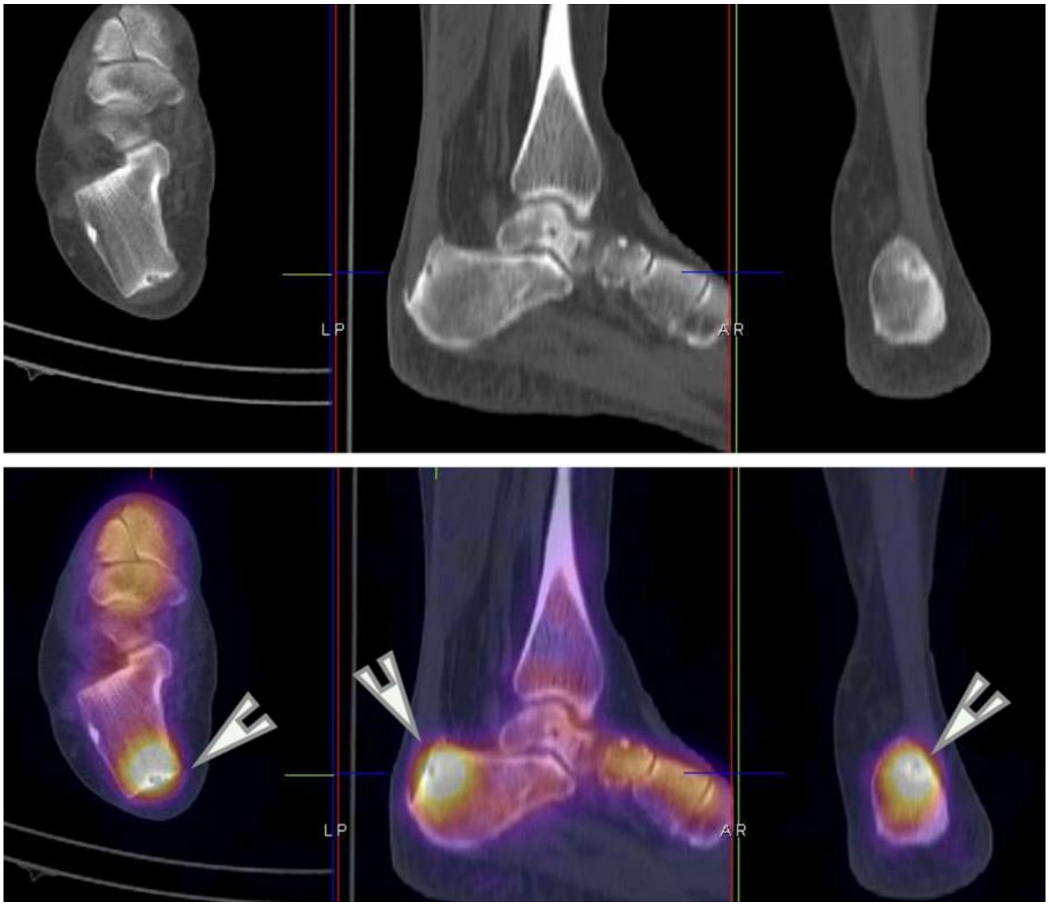


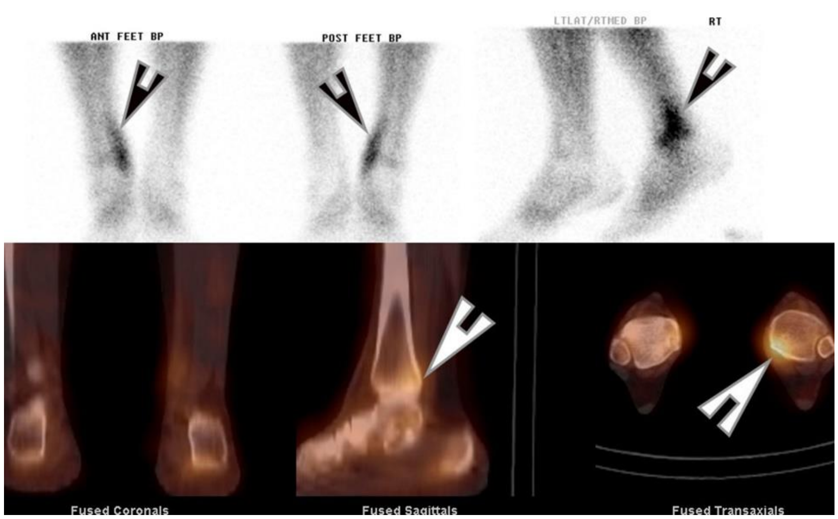
Figure 11. Direct muscle bruising with a calcified hematoma and increased uptake in the region of the iliotibial tract (arrowheads) in an older male who was accidentally kicked during a football tackle. The inset image is of the planar study in the anterior and posterior projections. The larger background image is the coronal slice from the fused SPECT/CT images.

TENDON AND ACCESSORY OSSICLES

Chronic tendon injuries have predominantly been reported in the lower limbs due to recurrent loading of the structures without adequate time for healing. These injuries dominate mainly professional sporting endeavours and less often in amateurs. The Achilles tendon, tibialis posterior, patellar and quadriceps tendons are the most commonly affected followed by the supraspinatus and common wrist extensors in the upper limb[28]. Tendinopathy has been redefined over the years and the assumption of chronic inflammatory change has largely been replaced based on human and animal biopsies that show both peri-tendinitis and a failure of healing[29]. The most common tendon injury amongst athletes is Achilles tendinopathy. There has been an increasing incidence of this injury over the past 35 years[30] and is most commonly imaged with either MRI or ultrasound but is frequently found as an asymptomatic but nascent injury on bone scintigraphy (Figure 12A). Tibialis posterior tendinopathy/ tenosynovitis is the second most common chronic injury and may be difficult to diagnose as symptoms are often vague, as presentation is with medial foot pain (Figure 12B). This tendon can be found in association with an accessory navicular[31] and may lead to injury of the synchondrosis (Figure 13 & 14). The os peroneum (Figure 15A) is an accessory bone located within the peroneus longus tendon, adjacent to the cuboid which may also sustain a similar injury[32], leading to increased uptake on scintigraphy (Figure 15B). It is prevalent in 26% of normals with the accessory navicular being present in 21%[31]. A similar pattern of increased uptake of tracer in association with impingement may also be present with the os trigonum in the posterior impingement syndrome of the ankle (Figure 15C). It is more rarely apparent with the os talotibiale in the anterior impingement syndrome of the ankle (Figure 15C).



<u>Figure 12A.</u> Severe Achilles tendinopathy. Intense uptake is apparent in the posterior and superior aspect of the calcaneum (arrowheads) in the fused SPECT/ CT images in the lower panel. Soft-tissue thickening and calcification of the tendon may be apparent in the CT study.



<u>Figure 12B.</u> Tibialis posterior tendinopathy/tenosynovitis. The upper panel demonstrates the intense hyperemia in the distribution of the tibialis posterior tendon as it curves around the medial malleolus of the right foot (arrowheads). The only abnormality in the late images, as demonstrated in this SPECT/CT study, is of secondary uptake adjacent to the tendon along the posteromedial aspect of the distal tibia.

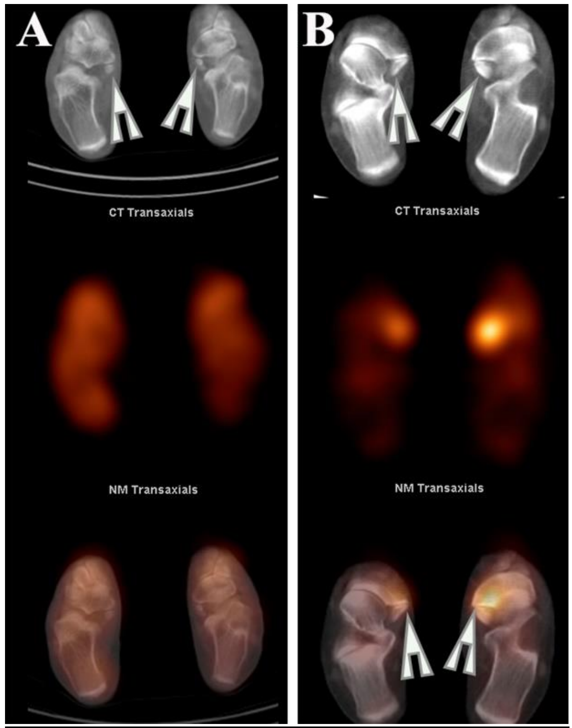


Figure 13. Accessory navicular syndrome (SPECT/ CT). Panel A demonstrates the normal appearance of the os naviculare which is located within the tibialis posterior tendon (arrowheads). Panel B shows the result of repetitive injury and disruption of the accessory bone from the medial edge of the navicular on both sides. There is intense increase in uptake of tracer on the symptomatic left-side (arrowheads) more than the right-side which was asymptomatic.

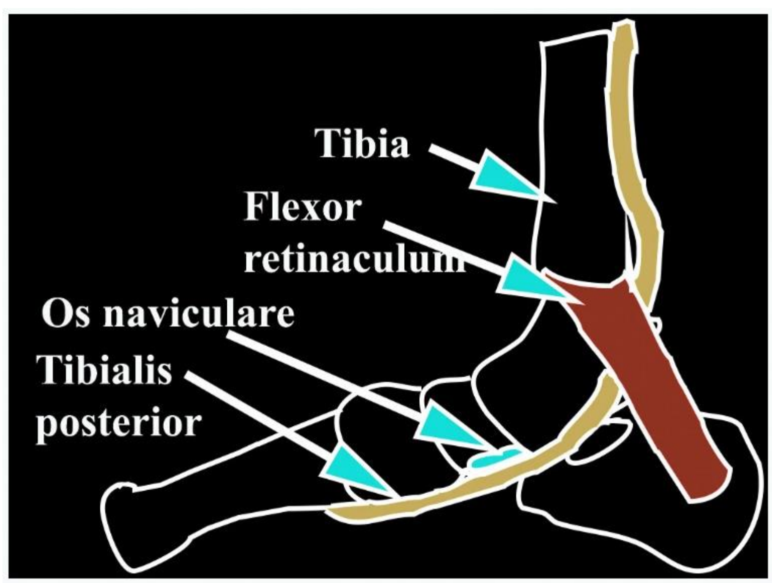


Figure 14. Anatomy of the tibialis posterior and its relationship with the os naviculare. The graphic illustrates the course of the tibialis posterior tendon beneath the flexor retinaculum and its insertion into the base of the metatarsal. The os naviculare is contained within the tendon and has either a bony or fibrous connection with the adjacent navicular.

Figure 15A. Plain film appearance of the os peroneum and its relationship with the cuboid (arrowhead).

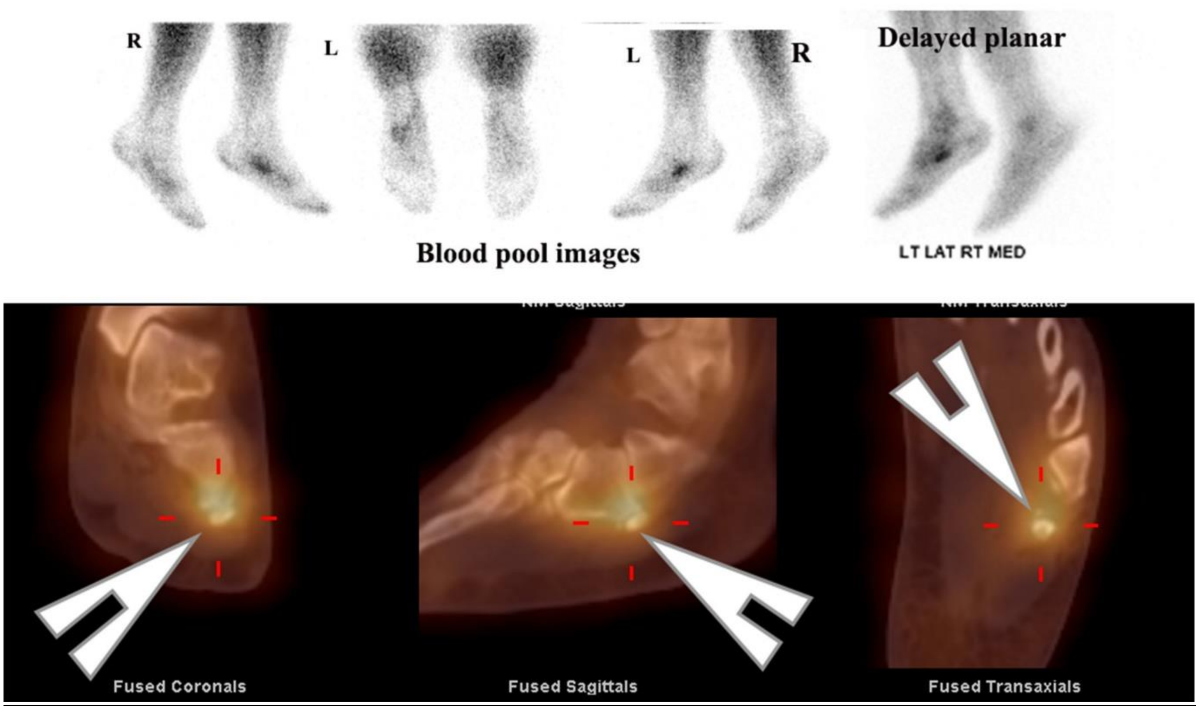


Figure 15B. Os peroneum. The os peroneum is an accessory bone that is within the peroneus longus tendon, immediately adjacent to the cuboid bone with which it has a fibrous or bony connection. Repetitive injury can also lead to injury to the connection with the cuboid and present with pain in the lateral aspect of the foot. This is demonstrated in the planar images as intense hyperemia and uptake in the distribution of the tendon and is identified as focal uptake within the os peroneum in the fused SPECT/CT images in the panel below (arrowheads).

Figure 15C. Anterior and posterior ankle impingement in a long-jumper. Intense uptake in apparent in the posterior aspect of the ankle in association with an os trigonum (arrowhead) and with a bone spur (arrow) in association with anterior impingement.

Most ligament injuries are in the acute setting and if occult may be detected later as avulsion injuries of bony structures. These injuries are mostly imaged with CT or MRI but may be an incidental finding on later bone scintigraphy.

MISCELLANEOUS SOFT-TISSUE INJURIES

Most other soft-tissue injuries are almost always imaged with MRI, CT or ultrasound. One of the most common types of bursitis is trochanteric bursitis. The aetiology remains uncertain but is thought to be due to overuse. It has also been associated with lower back pain in 45% of patients. Scintigraphy may also predict the response to glucocorticoid injection into the bursa in this group[33, 34]. Multiple descriptions of bursae around the hip have enumerated between 14 and 21 bursae[35]. Three constant bursae have been reported around the greater trochanter with most common involvement with the sub-gluteal bursa which lies beneath the gluteus medius muscle and is located posterior and superior to the proximal edge of the greater trochanter. Calcification around the greater trochanter has been reported in up to 40% of patients with trochanteric bursitis[35]. Trochanteric bursitis is a frequent finding on bone scintigraphy when evaluating lateral hip pain and the specificity has been significantly improved with SPECT/CT imaging (Figure 16).

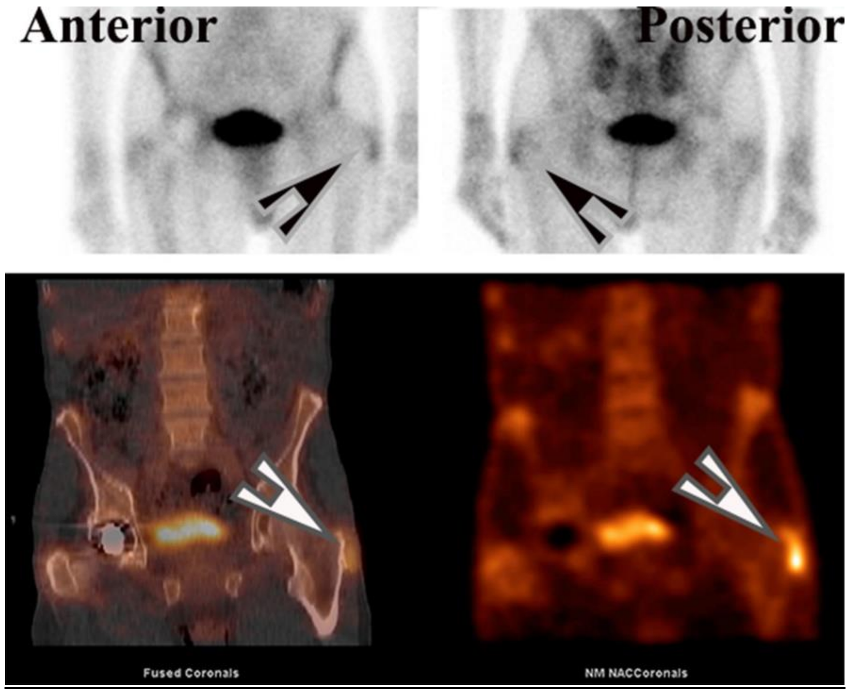


Figure 16. Trochanteric bursitis. The upper panel demonstrates focal uptake around the left greater trochanter in the anterior and posterior projections (arrowheads). The lower panel shows the fused SPECT/CT and SPECT images where there is intense uptake of tracer in the posterolateral edge of the left greater trochanter (arrowheads).

Chronic compartment syndrome generally involves the lower limbs and in particular the anterior compartment muscles around the tibia[16, 28]. A number of reports have shown a small role for scintigraphy in the diagnosis, but this has largely been replaced by either MRI or direct physical pressure measurements from the suspected compartment. It may be diagnosed by bone scintigraphy with uptake in necrotic muscle[36] or by exercise-induced reversible ischemia in the compartment[37].

Injuries to bone

ACUTE FRACTURES

Most Acute fractures are easily diagnosed by either plain film radiography or CT scanning. On rare occasions, particularly in the bones of the hands and wrists these injuries may not be clearly identified and MRI or bone scintigraphy are utilised and have been reported to have equivalent sensitivity and specificity for the detection of fractures[38]. It is estimated that 25% of all acute sporting injuries occur in the hands and wrists[39]. The major sports with hand injuries are in the martial arts, boxing or any contact sport. A sample of SPECT/ CT images of wrist fractures is illustrated in Figure 17 and 18.

Acute fractures in children are problematic when there is injury to the growth plate by the fracture line and may lead to subsequent growth disturbances. These injuries are classified in the Salter Harris system (Figure 19). A scintigraphic example of the complication of a type 1 fracture is shown in Figure 20 and 21.

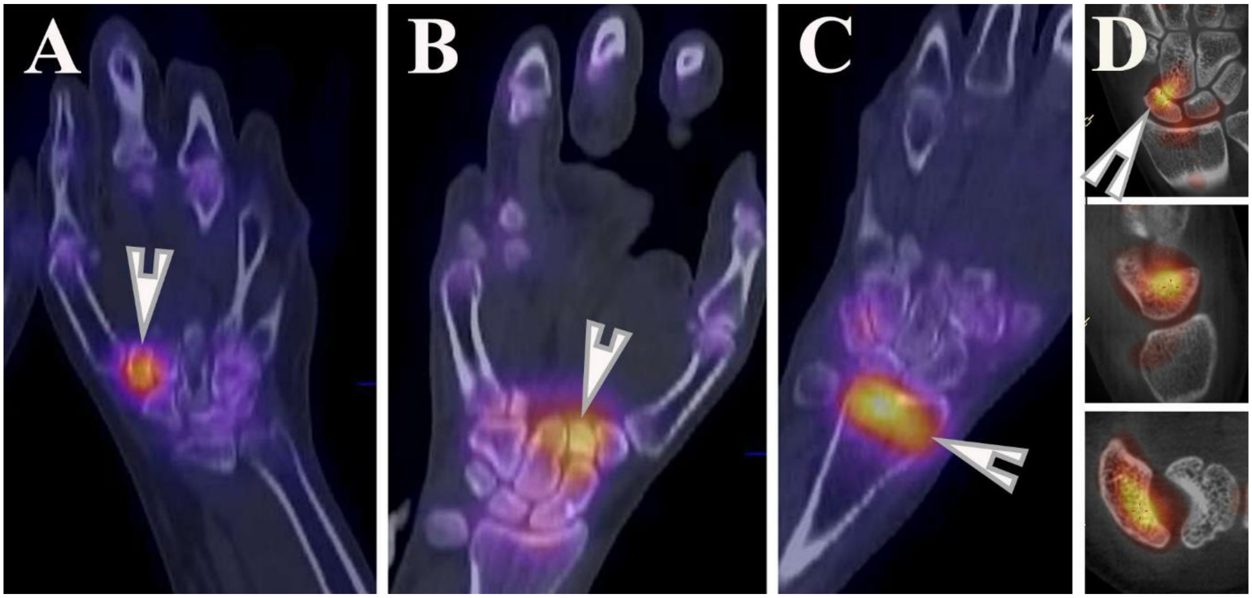


Figure 17. SPECT/CT fusion images of acute fractures of the wrist. Fractures of the A. Trapezium B. Trapezoid C. Distal radius D. Scaphoid.

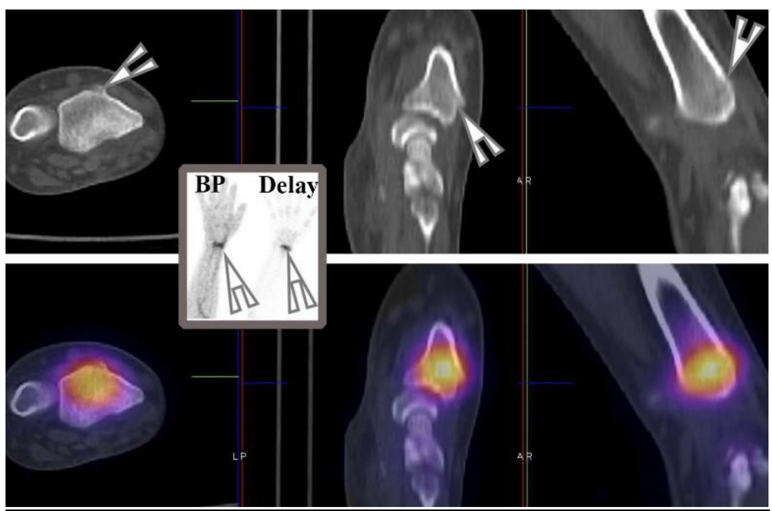


Figure 18. SPECT/CT imaging of Salter-Harris Type 2 fracture of the radial growth plate. The inset image shows the planar blood pool (BP) and delayed images there is hyperemia in the radial growth plate and the delayed image shows intense uptake at the site (arrowheads). This fracture is well delineated in the CT [arrowheads] with intense uptake in the corresponding fused image.

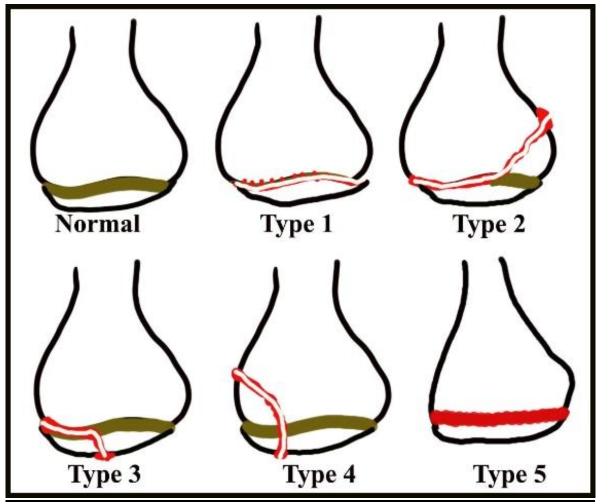


Figure 19. Graphic of Salter Harris classification of growth plate fractures. Type 1 is a fracture through the growth plate with displacement of the epiphysis. Type 2 is a fracture which extends from the metaphysis into the growth plate. Type 3 is a fracture which extends from the epiphyseal surface into the growth plate. Type 4 is a fracture that extends from the metaphysis across the growth plate into the epiphysis. Type 5 is a crush fracture of the growth plate.

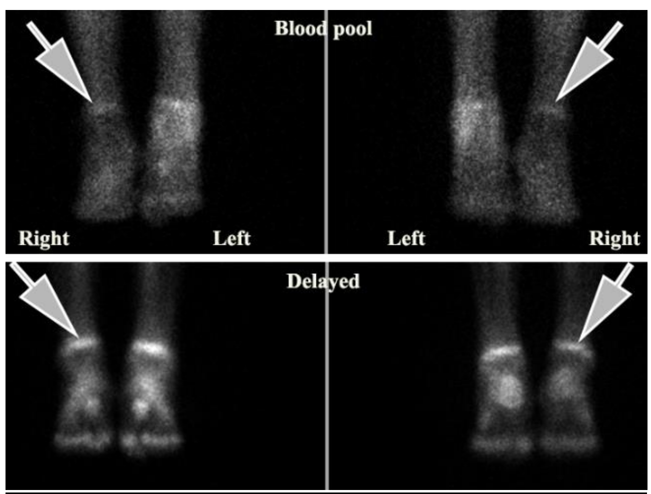


Figure 20. Planar images of a Type 1 Salter Harris fracture of the right tibial growth plate (arrow) with a permanent injury to the growth plate which is reflected in the diminution in blood flow and the reduced intensity of uptake in the growth plate in the delayed study.

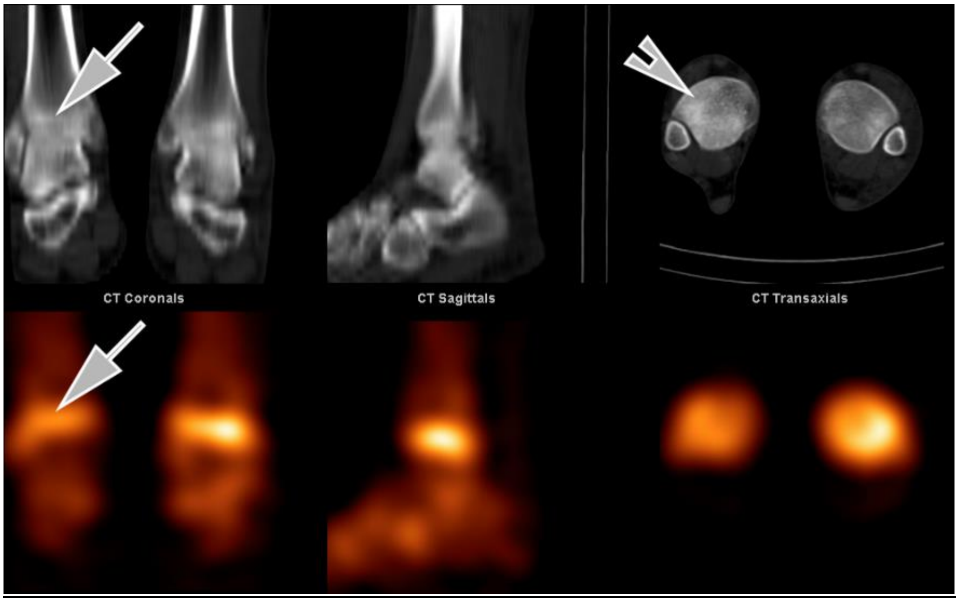


Figure 21. SPECT/CT of the injury in Figure 21. The CT study shows significant sclerosis of the anterolateral aspect of the right tibial growth plate (arrowhead) with significant diminution of the pattern of uptake in the corresponding scintigraphic SPECT images (arrow). The pattern of injury may lead to significant abnormalities in growth of the long bones, depending upon the age of the patient at the time of the injury.

BONE BRUISING

Bone bruising is fundamentally a contusion of bone and lies in the spectrum of occult bone injury where the principal pathology lies in the cancellous bone without obvious injury to the cortical structures. There is bleeding, microfractures and oedema due to the microscopic compression fractures.[40] It is generally characterised as high-signal on the T2 sequence of MRI and has been mostly described in the knee in association with other soft-tissue injuries such as to the cruciate ligaments,[41] although other bones such as the elbow and calcaneum are also involved. Healing usually occurs at 2-4 months.[42] Bone scintigraphy has been reported as having good utility in comparison to MRI and arthroscopy.[43] Scintigraphic and MRI images of bone bruising in the knee are shown in Figure 22 and 23.

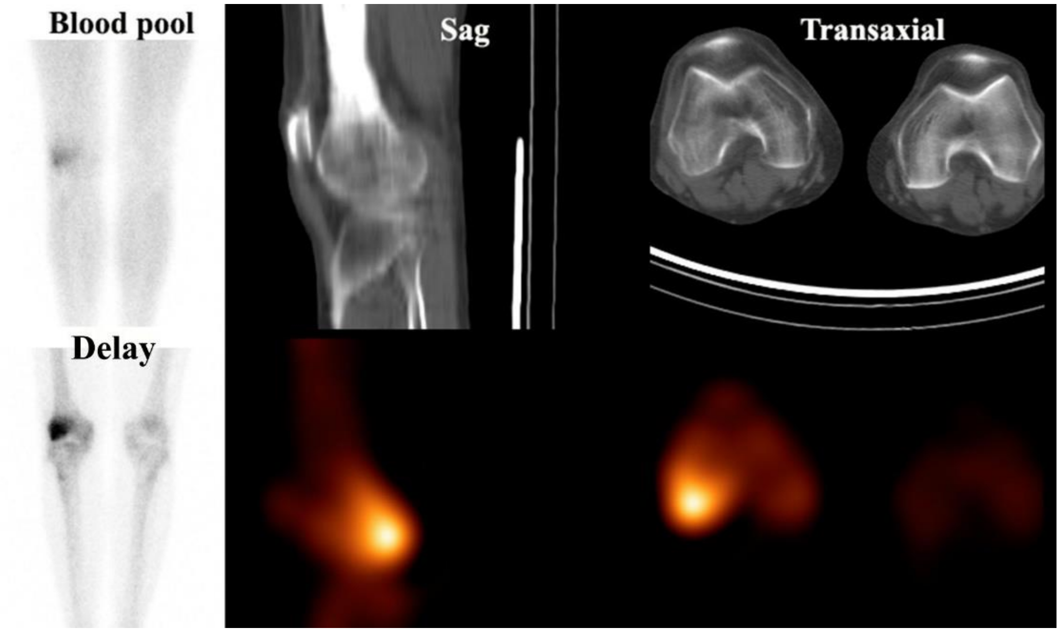


Figure 22. Scintigraphy of bone bruising. The injury was found in a footballer who took a direct blow to the back of the right knee. Plain film and CT were reported as normal. The patient was referred for scintigraphy where the blood pool image shows focal hyperemia in the posterior aspect of the right lateral femoral condyle. The delayed image shows quite intense uptake at the same site. The SPECT/CT images show focal increased uptake of tracer in the posterior aspect of the right lateral femoral condyle without a concomitant CT scan abnormality, in keeping with the diagnosis of bone bruising.

Figure 23. MRI of bone bruising (PD Fat sat image). The coronal image demonstrates high signal arising from the lateral aspect of the left proximal tibia at a site of direct injury (arrowhead). Significant high signal is also apparent in the distal insertion of the iliotibial band.

STRESS REACTIONS AND STRESS FRACTURES

Bone stress is a normal physiological process if coupled with adequate time for healing and recovery. It is when the time element is compromised that both stress reaction and fracture may occur. However, the response to stress is modulated by many other factors, some of which remain unknown but include genetic, nutritional, hormonal and physical conditioning[28]. Stress reactions are best viewed as a precursor to stress fracture and are characterised by sclerosis without clear-cut cortical infraction[44], prior to the crossover from the elastic range of bone into the plastic range (Figure 3)[45]. The term is somewhat of a misnomer as on histologic examination, it is often characterised by multiple microfractures in the subcortical tissues[45]. An example of a stress reaction is shown in Figure 24 in the pars interarticularis of L4 but has been reported in multiple other bones, especially in the feet. Numerous publications have quoted an incidence of fractures by sport and this may well be based upon the increasing participation in both amateur and professional sport. However, the vast majority of stress fractures are in runners, as illustrated in Figure 25 (Derived from Jones et al.[45]) and predominantly involve the lower limbs.

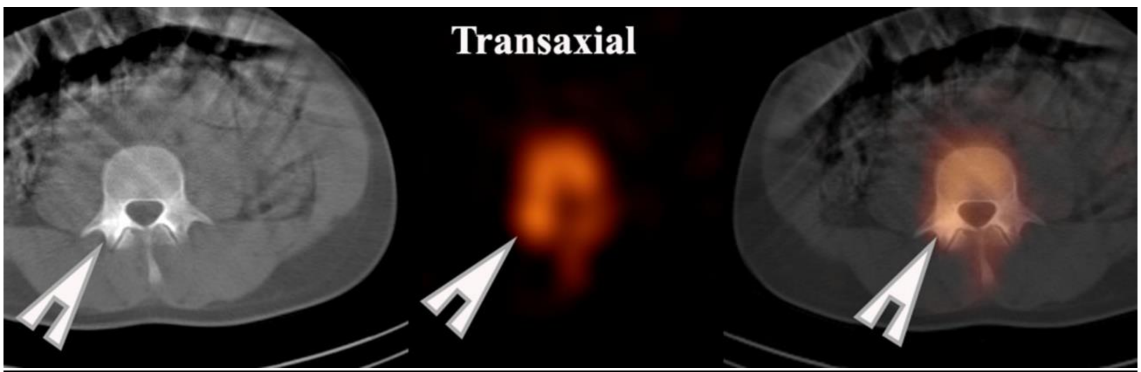


Figure 24. Stress reaction. This patient was a fast-bowler who presented with back pain. Plain film had been reported as normal. The SPECT/CT images of the transaxial projection demonstrates focal increased uptake of tracer in the right pars interarticularis of L4 (arrowheads) with the CT study showing diffuse sclerosis of the pars without evidence of a fracture.

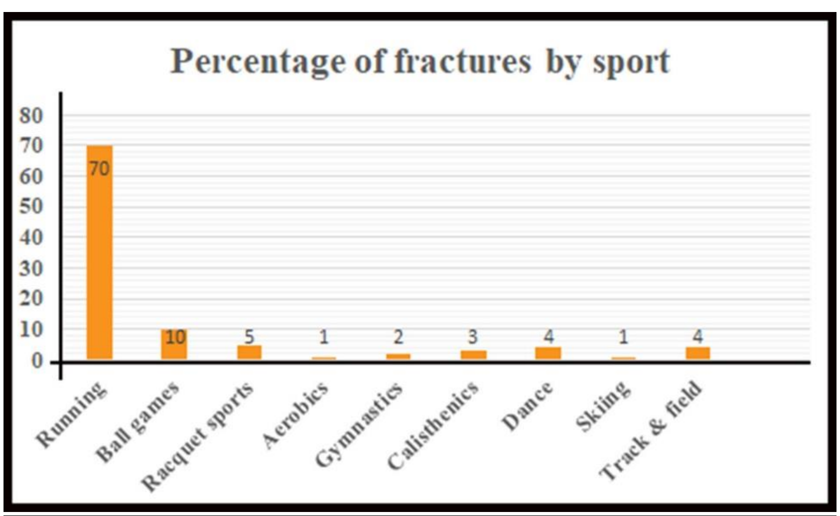


Figure 25. Graph of fractures by sport. The graph demonstrates that the majority of fractures occur in runners with other sports contributing a smaller minority, except for ballgames which contribute approximately 10% of fractures. This graph is a composite of data presented by Jones et al.[45]

MEDIAL TIBIAL STRESS SYNDROME (MTSS)

Shin splints were first described by Devas as a muscular traction injury in 1958[46]. The term has been replaced by the concept of the medial tibial stress syndrome which is now thought to be musculotendinous inflammation due to overuse of the foot flexors after the exclusion of fracture or ischaemic disorders of the calf[47]. However, several studies implicates a traction injury of the soleus and flexor hallusis longus and possibly the flexor digitorum longus with a claw-toe deformity[48].

The characteristic bone scan appearance is of linear uptake along the periosteal surface of the affected tibial cortex[49, 50]. The key is exclusion of a stress fracture. Interestingly, 40% of runners with a weekly distance of 80-100 km have been shown to have MRI findings of the MTSS while asymptomatic[51]. Figure 26 demonstrates the coexistence of a stress fracture and MTSS while Figure 27 shows bilateral MTSS. The clinical difference has little utility in separating the two entities.

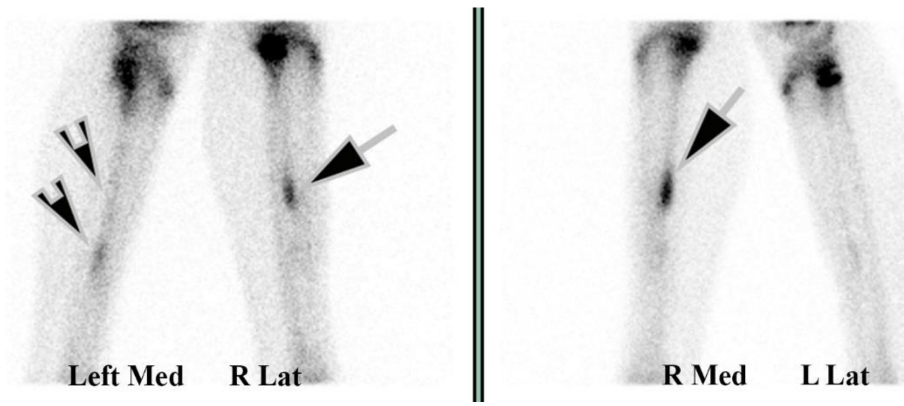


Figure 26. Planar images from a runner with bilateral shin pain. The delayed image of the lower limbs demonstrates a stress fracture (arrow) and long-segment uptake characteristic of the medial tibial stress syndrome (shin splints) which is indicated by arrowheads.

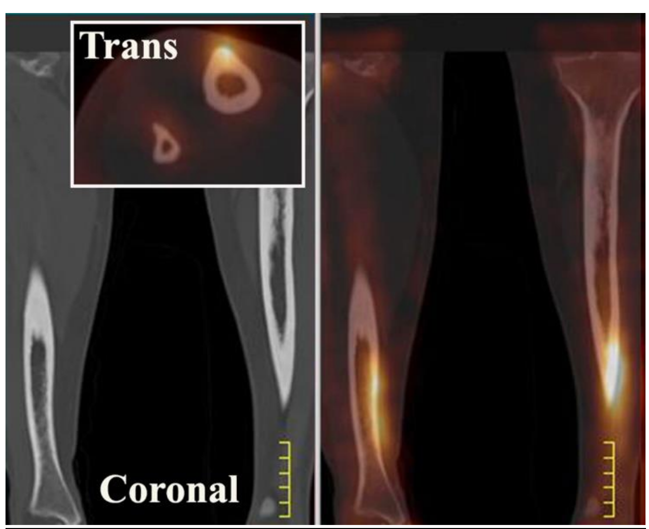


Figure 27. Medial tibial stress syndrome. The SPECT/CT images show long-segment uptake in the distal tibiae, where there is no significant alteration in the cortex in the accompanying CT study, apart from peri-cortical uptake in the fused scintigraphic image.

STRESS FRACTURES IN THE LOWER LIMBS

The incidence of stress fractures in the general population is estimated at approximately 1% but has been reported in up to 20% of runners[52]. More than 90% of stress fractures affect the lower limbs[53]. As a general rule, compressive stresses are better tolerated than tensile stresses and the shock absorbing capabilities of muscle strength and endurance are a critical issue. The cycling frequency of the stress is also critical if it impinges on the healing and recovery time in the particular bones under stress. Bone turnover in the long-bones of the lower limbs has been estimated at less than 1% per year of bone mass and may favour the development of micro-damage which eventually leads to fracture[54].

Stress fracture by site and type of bone involvement is shown in Table 1 and is derived from a review paper generated in time for the London Olympics[55].

Table 1 Incidence of lower limb fractures by site, sport and bone structure

Site	Percentage	Sporting association	Bone type
Metatarsals	8-24.6	2nd and 3rd metatarsal distal shaft and neck. Long-distance runners	Cortical
Tarsals	7.0-25.3	Calcaneum – Long-distance runners, jumpers Navicular – track & field, rugby, basketball Talus – long distance runners, gymnasts	Trabecular
Tibia	16.0-49.1	Transverse (posterior) – long-distance runners Transverse (anterior) – jumpers Longitudinal – long-distance runners	Cortical
Fibula	1.3-12.0	Long-distance runners	Cortical
Femur	4.2-48.0	Neck – long-distance runners Shaft – long-distance runners, gymnasts	Trabecular Cortical
Pelvis	1.3-5.6	Sacrum – long-distance runners Apophyseal – soccer players, gymnasts Pubic rami – long-distance runners	Trabecular Cortical Cortical

(Derived from Liong & Whitehouse [55])

METATARSAL FRACTURES

Metatarsal stress fractures are probably the most common site of stress fracture in the foot. In one study of 295 subjects, 28% of 339 stress fractures were in the metatarsals.[56] The most common causation is high impact to the foot in sports involving running and jumping. The majority of metatarsal fractures (~90%) are reported in the second (Figure 28) and third metatarsal bone with some unusual activities leading to fracture.[57] High levels of stress are transmitted through the second and fifth metatarsal bones [58] with the second having the highest transmission. Two types of fracture are commonly reported in the fifth metatarsal, either involving the shaft or the more proximal injury, the Jones fracture.[59]

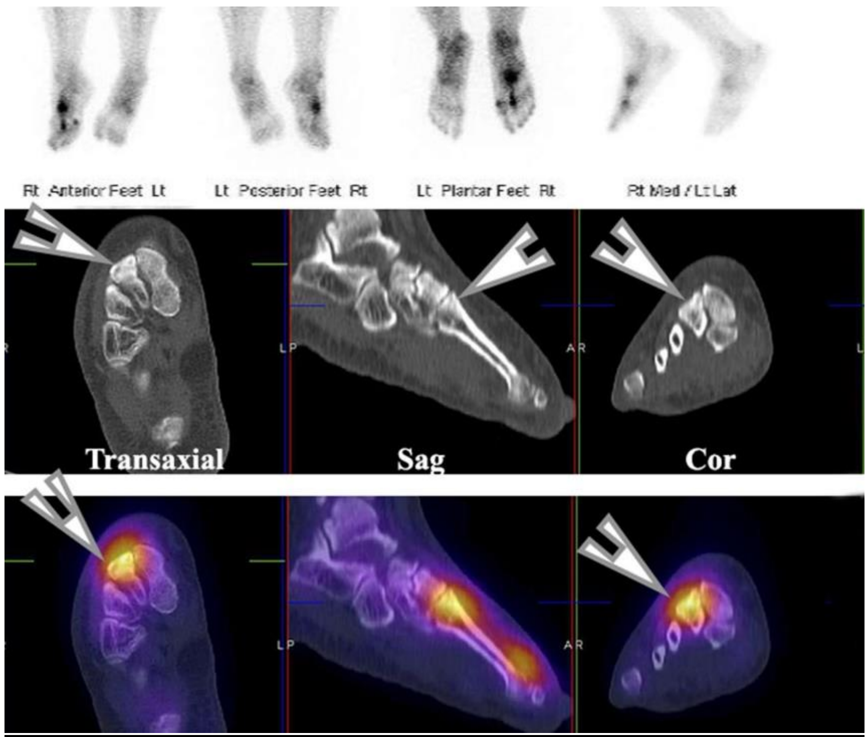


Figure 28. Stress fracture of second metatarsal bone. The upper panel shows intense increase in uptake extending along the cortex of the right second metatarsal bone. The CT and fused images demonstrate cortical thickening in the dorsal aspect of the second metatarsal bone [arrowheads]. The sagittal CT image shows a fine lucent fracture line extending through the proximal dorsal cortex.

CALCANEAL FRACTURES

Calcaneal fractures are considered the most common fracture of the tarsal bones, probably accounting for approximately 2% of all fractures. The majority of calcaneal fractures are acute with stress fractures occurring principally in runners. The trabecular pattern in the calcaneum together with the more thickened cortical structures that buttress the articular facets determine the patterns of fracture. Most of these fractures are intra-articular (75%), the remainder being classified as extra-articular as they do not involve the posterior facet. The typical calcaneal stress fracture occurs vertically through the posterior aspect of the bone and is well illustrated in Figure 29.

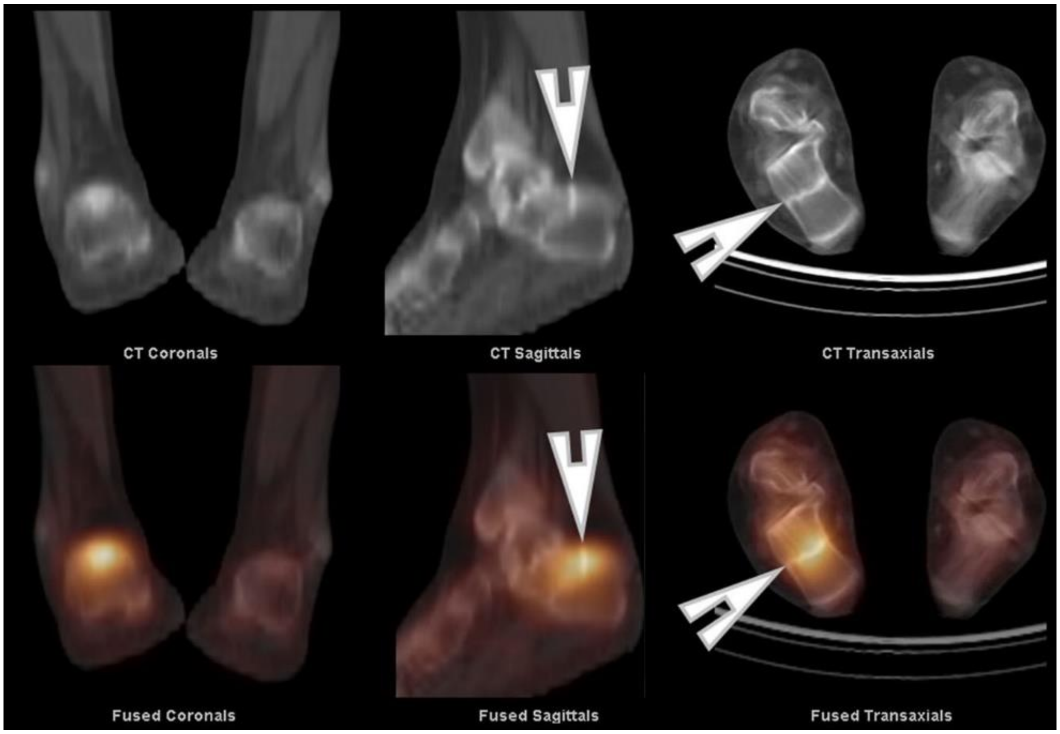


Figure 29. SPECT/CT images of a stress fracture of the right calcaneum in a runner. The CT image shows a sclerotic vertical fracture line extending through the posterior aspect of the right calcaneum (arrowheads). The fused image demonstrates intense increase in uptake at the site.

INJURIES AROUND THE ANKLE

Ankle injuries are the single most common sporting injury as reported in a study of 70 different sports, where ankle injury was reported in 24[60]. Occult osteochondral injuries of the ankle have been found in up to 50% of acute ankle sprains and fractures (Figure 30), most often in association with sporting injuries[61]. The average age for these injuries ranges between 20 and 30 years with a male preponderance of 70% and bilateral involvement in 10%[61]. One study of 500 patients with osteochondral lesions found that 98% of the lateral talar dome lesions and 70% of medial talar dome lesions were associated with a history of trauma[62]. The current use of CT, MRI and bone scintigraphy with SPECT/CT detects these occult lesions much more frequently and easily than with plain film radiography. Osteochondral lesions of the tibial plafond are relatively rare (Figure 31) in comparison with the talar dome. This may reflect the thickness and mechanical properties of the cartilage as well as the better blood supply to the tibia. Injury to the medial malleolus and medial talus are even more unusual (Figure 32). Ankle sprains can also lead to fractures of the adjacent tarsal bones (Figure 33) and fibula.

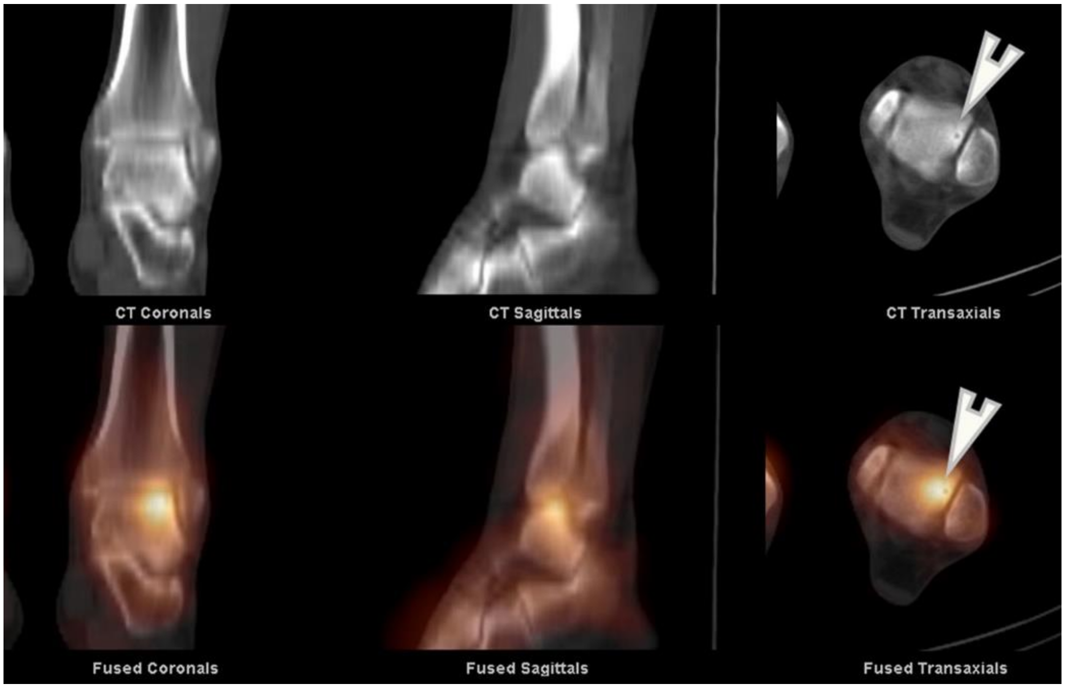


Figure 30. SPECT/CT images of an osteochondral injury of the medial talar dome. The fused images in the lower panel demonstrate intense increase in uptake of tracer in the medial aspect of the talar dome (arrowhead). The corresponding CT study in the upper panel shows a region of sclerosis surrounding an erosion of the medial talar dome. The injury occurred several months before in a footballer who complained of persistent pain following an ankle sprain.

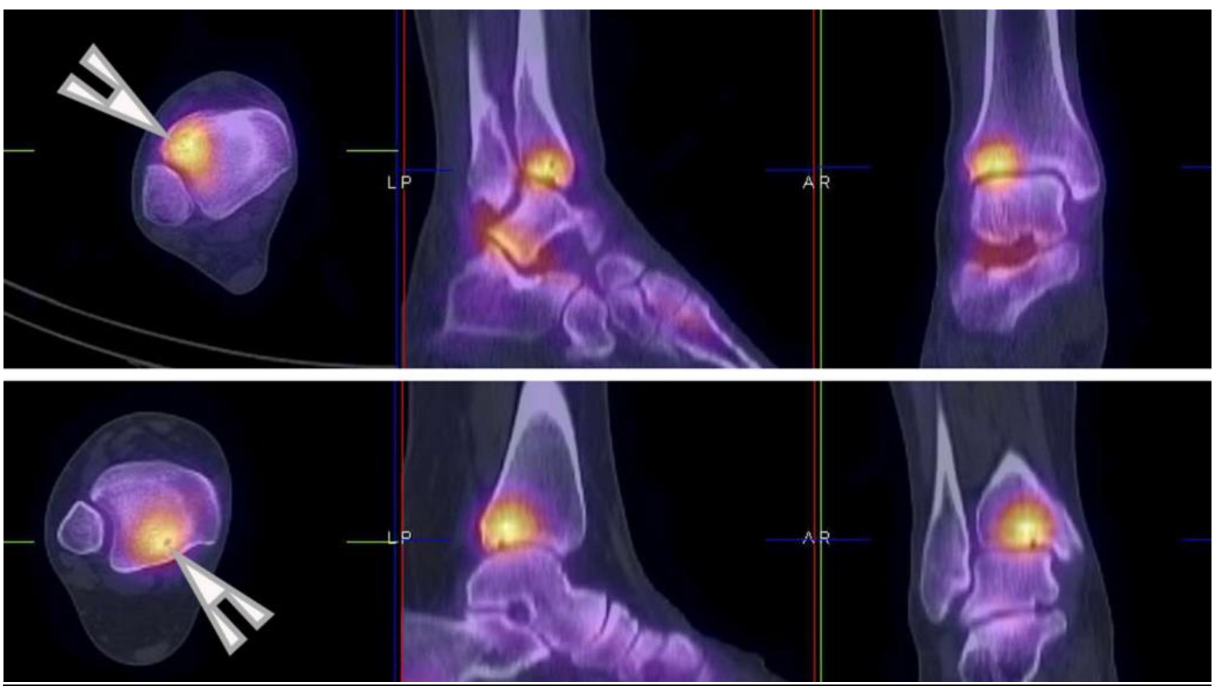


Figure 31. Fused SPECT/CT of osteochondral injuries of the tibial plafond. The upper panel shows a osteochondral injury of the posterior aspect of the lateral tibial plafond in association with sclerosis and a small osteochondral injury (arrowhead). The lower panel demonstrates an osteochondral injury of the posterior tibial plafond with associated sclerosis and an osteochondral erosion (arrowhead).

Figure 32. Complex stress fractures of the tibia. The patient was a runner who presented with pain in the ankle and in the distal aspect of the left tibia. Plain film had been reported as normal. A. The planar images in the upper panel demonstrate focally intense increase in uptake of tracer in the posteromedial cortex of the left distal tibia [arrow] and in the medial malleolus [arrowhead] B. The fused SPECT/CT images of the distal tibia demonstrate intense focal uptake of tracer and cortical thickening, in keeping with a stress reaction [arrows] C. The lower two panels however demonstrate intense uptake of tracer in the anteromedial aspect of the medial malleolus with the CT study demonstrating lucency of the posterior aspect of the medial malleolus [arrowhead] in keeping with osteolysis at a site of persistent stress on the medial malleolus.

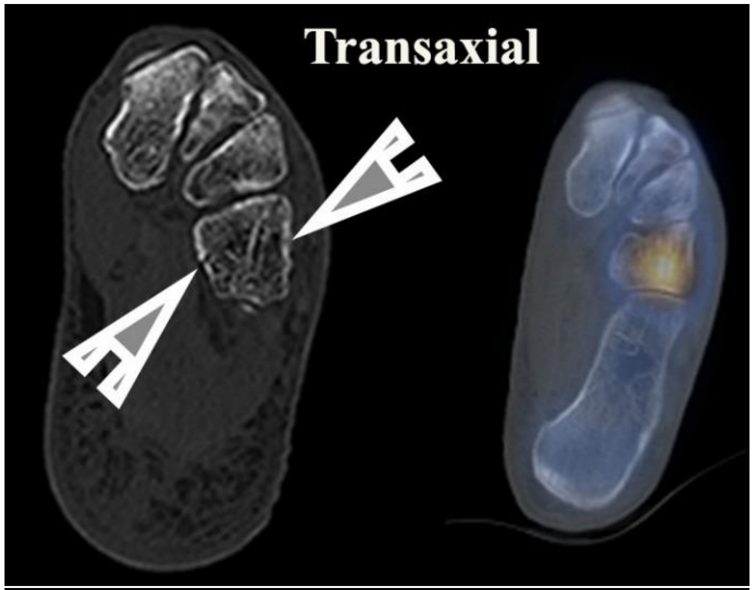


Figure 33. Acute fracture of the cuboid. The patient was a soccer player who had a complex injury to the ankle and had difficulty weight-bearing. Plain films of the foot had been reported as showing no fracture with subsequent referral for bone scintigraphy. The fused SPECT/CT images demonstrate intense uptake of tracer in the cuboid and the CT study demonstrating a clear fracture line through the cortex of the cuboid (arrowheads).

TARSAL COALITIONS

Tarsal coalition is the congenital fusion between adjacent tarsal bones that changes the biomechanics of the foot and leads to early degenerative changes in other joints due to rigidity of the articulation. There is a failure of differentiation and segmentation of embryonic mesenchyme with an autosomal dominant inheritance pattern[63]. The articulations are classified as osseous (synostosis) or non-osseous (cartilaginous or fibrous). Autopsy studies indicate that the incidence may be as high as 12.7% with 90% involving talocalcaneal (**Figure 34**) and calcaneonavicular coalitions. These changes increase the likelihood of injury during sport and should be considered as a predisposing factor to injury.

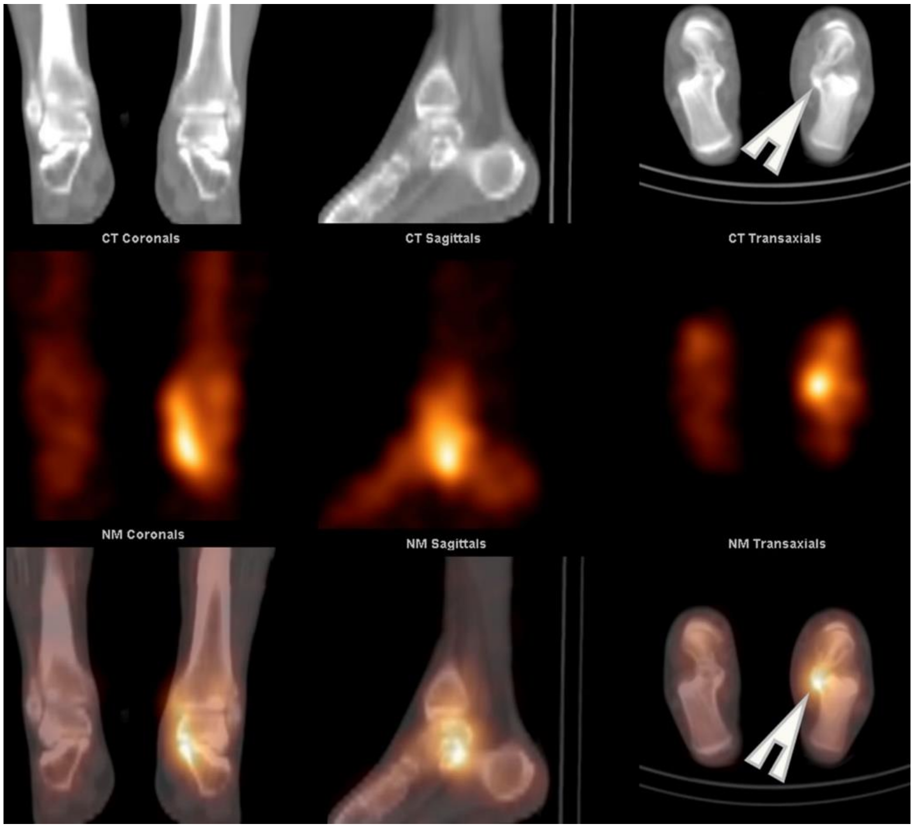


Figure 34. Fracture through a talo-calcaneal coalition. The SPECT/CT images demonstrate intense focal uptake of tracer at a site of coalition between the medial aspect of the left talus and the calcaneum, with the CT study showing a sclerotic region within the coalition bar, corresponding to the site of uptake [arrowhead], suggesting a response to stress and subsequent fracture of the coalition. The stress is thought to occur in response to the rigidity of the subtalar joint.[63]

STRESS FRACTURES OF THE TIBIA AND FIBULA

Stress fractures of the tibia and fibula are increasingly reported as running and cycling become more popular as recreational past-times. Awareness of the diagnosis is leading to more rapid imaging and earlier diagnosis. One of the largest series reported the incidence of stress fractures of approximately 2% in 10,276 patient attendances at a sports medicine clinic in a 10 year period[64]. Average age of patients with stress fractures was 20.1 years, with 43% being 15-19 years. The distribution of stress fractures was 40% in the tibial shaft (Figure 35) and 5% in the fibula (Figure 36). These findings are similar to the reports of Hulkko et al [59] and Devas[65]. The most commonly reported sports included basketball, baseball, track and field, rowing, aerobics and soccer. Matheson et al [66] found that the tibia was the most common site (49%). Key elements were thought to be mechanical dysfunction, gait alterations, choice of foot-wear and the ground surfaces on which the activity occurs.

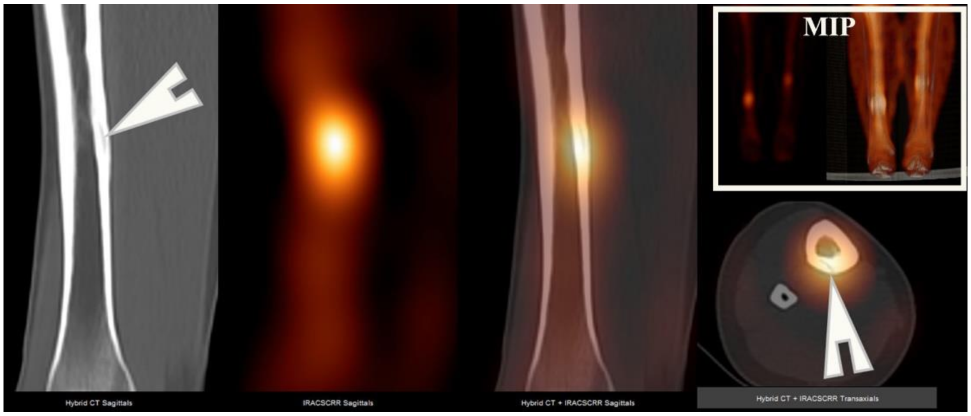


Figure 35. Bilateral stress fractures of the tibia in a long-distance runner. The inset maximal intensity projections (MIP) demonstrate intense focal uptake of tracer in the distal aspect of both tibiae, being more marked on the right side. The SPECT/CT images confirm intense increase in uptake of tracer in the posteromedial cortex of the right tibia with a lucent fracture line extending through the cortex (arrowheads).

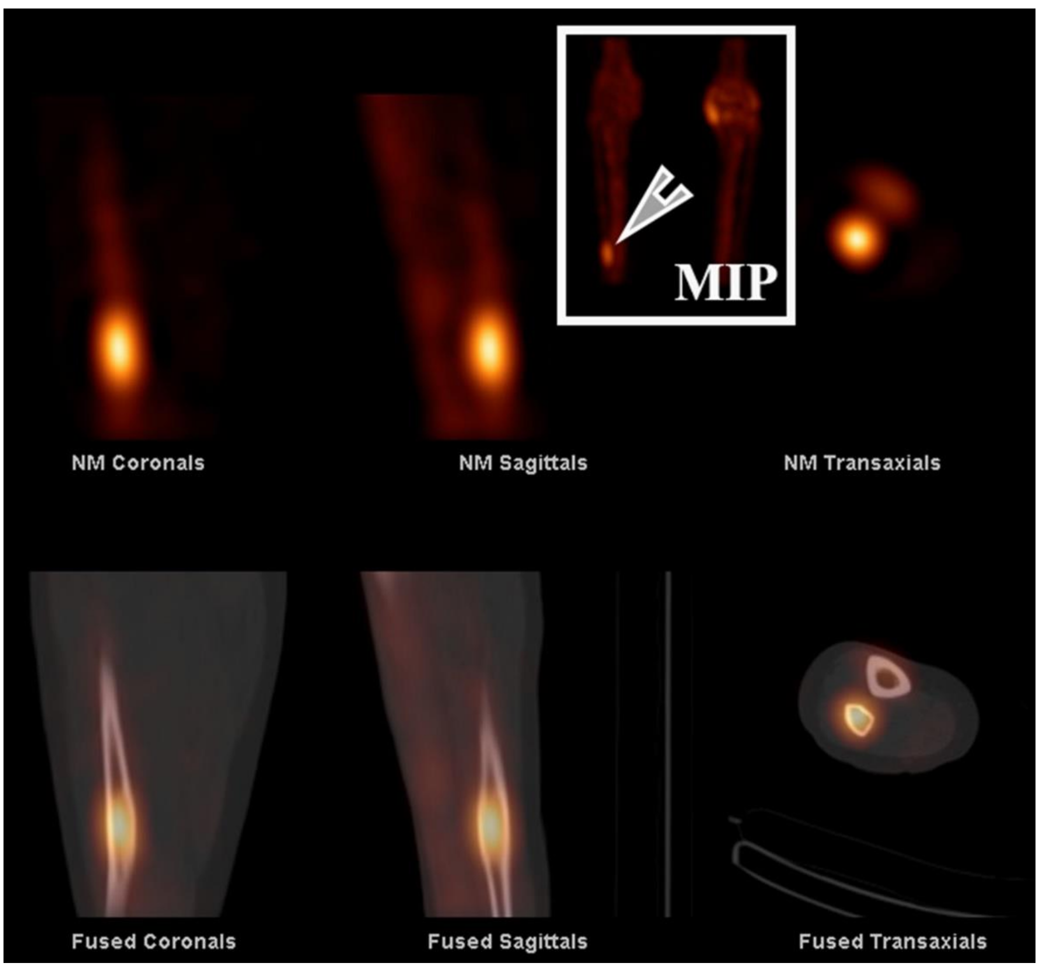


Figure 36. Stress fracture of the fibula. The inset MIP image demonstrates focal uptake of tracer in the distal aspect of the right fibula (arrowhead) in a medium-distance runner. The SPECT/CT images show intense focal uptake of tracer in the right fibula with cortical thickening (best seen in the fused transaxial image) but no clear-cut fracture line. The prolonged recovery time was more consistent with a fracture.

STRESS FRACTURES OF THE FEMUR

Stress fractures result from repetitive stress on normal bone and if continuous without time for healing leads to increased osteoclastic activity and eventual micro-trabecular fractures. Progression of the injury eventually leads to a cortical break[67]. The vast majority will occur in female athletes running medium-long distances in almost 90% of cases[68]. The most frequent symptom will be anterior thigh pain in 50% of cases. In cases where bone stock is normal, fracture generally occurs on the compressive or inferior side of the femoral neck (Figure 37 & 38)[69]. When bone stock is compromised, fractures occur through the tensile or superior portion of the femoral neck Figure 39 and may end up in the disastrous position of an impacted femoral neck fracture Figure 40 as happens in osteoporotic bone.

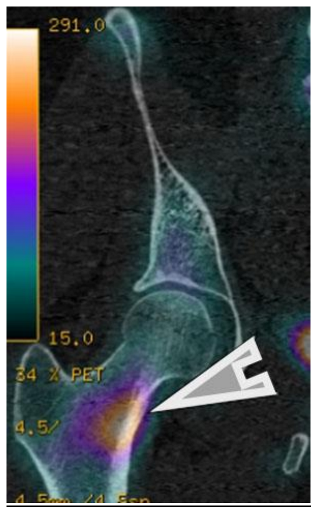


Figure 37. Fused SPECT/CT image of a typical stress fracture of the hip in a female long-distance runner. The more intense increase in uptake and cortical thickening is on the compression side of the femoral neck (arrowhead).

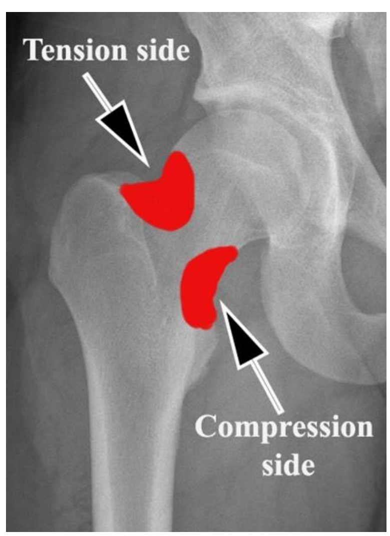


Figure 38. Illustration of the forces on the femoral neck. These superior side of the femoral neck is where tension forces are greatest while the inferior side is where the compressive forces are greatest. Fractures that occur on the compressive side are usually in patients with normal bone stock compared to the tension inside, where bone stock is compromised.

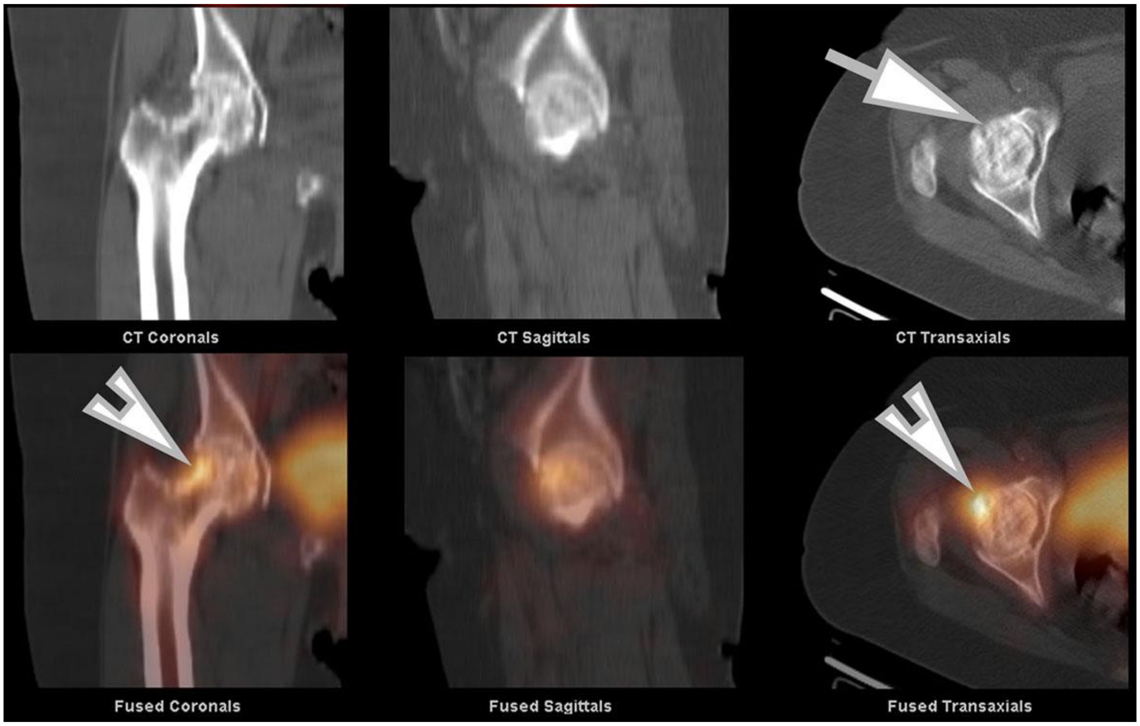


Figure 39. SPECT/CT images of a hip fracture in an osteoporotic female who commenced a fast-walking program. Focally intense increase in uptake is apparent in the superior aspect of the right femoral neck (arrowheads) with a clear-cut lucent fracture line through the superior femoral neck in the corresponding CT images (arrow).

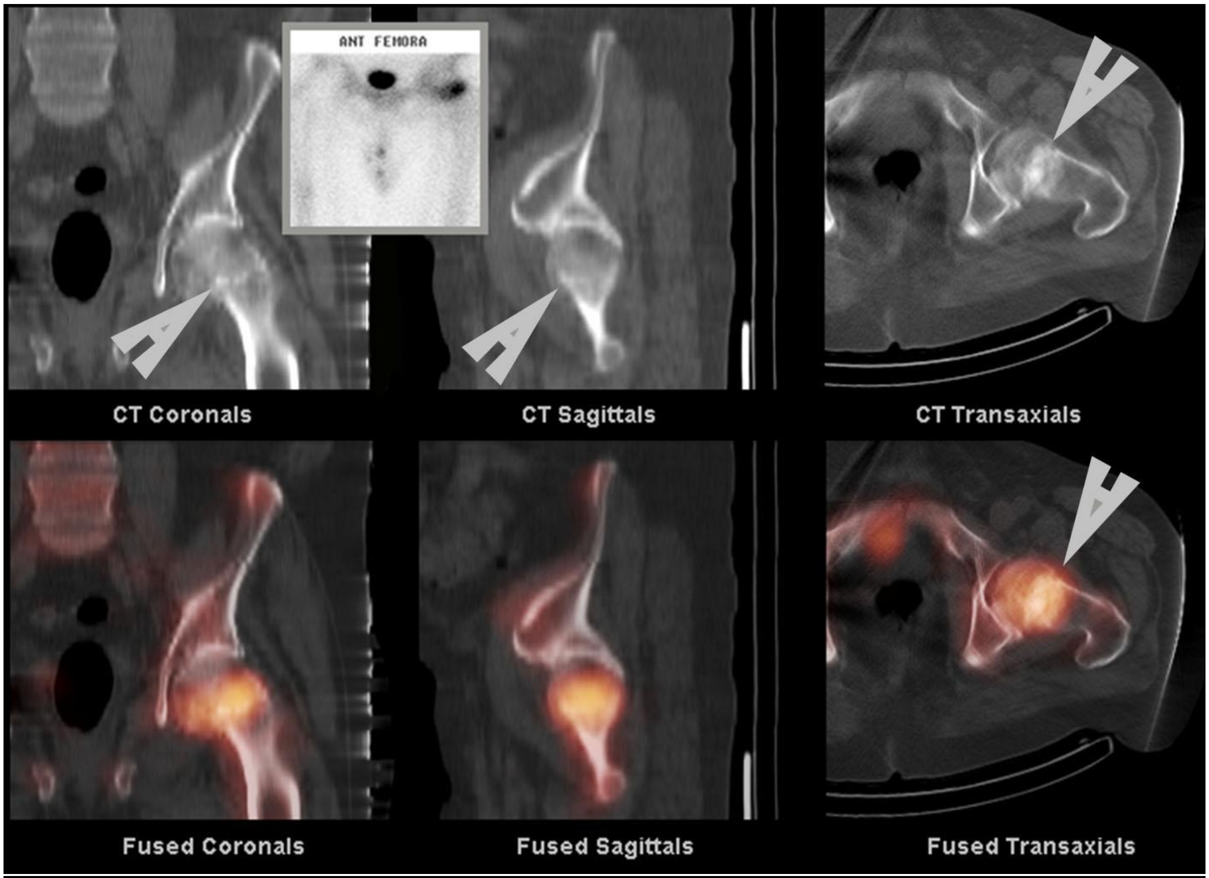


Figure 40. SPECT/ CT of hip fracture with impaction. A 70-year-old runner presented with progressively increasing pain in the left groin following a half-marathon. The SPECT/CT images demonstrated intense increase in uptake of tracer through a shortened femoral neck with the CT study showing an impacted sub-capital fracture (arrowheads). It is likely that the patient had compromised bone mineral density, predisposing to a fracture with subsequent impaction while running.

PELVIC STRESS FRACTURES

Fractures of the sacrum have largely been reported in female long-distance runners with a high prevalence of amenorrhoea which may compromise Bone mineral density[70,71]. However, several cases have also been reported in hockey players, basketball, tennis and volleyball[55]. Most plain film radiography is unproductive in up to 85% of sacral fractures[55]. Diagnosis is most reliant on MRI and bone scintigraphy with SPECT/CT (Figure 41). The presentation is usually with low back pain which may be lateralising or diffuse. However, a similar presentation may occur with pars interarticularis fractures (Figure 42), apophyseal fractures in adolescents, acute exacerbations of degenerative disease of the intervertebral discs and facet joints and the possibility of seronegative arthropathy with sacroiliitis or mechanical dysfunction of the sacroiliac joints should also be kept in mind. The array of diagnoses may be successfully made with MRI and in many cases with bone scintigraphy with SPECT/CT imaging.

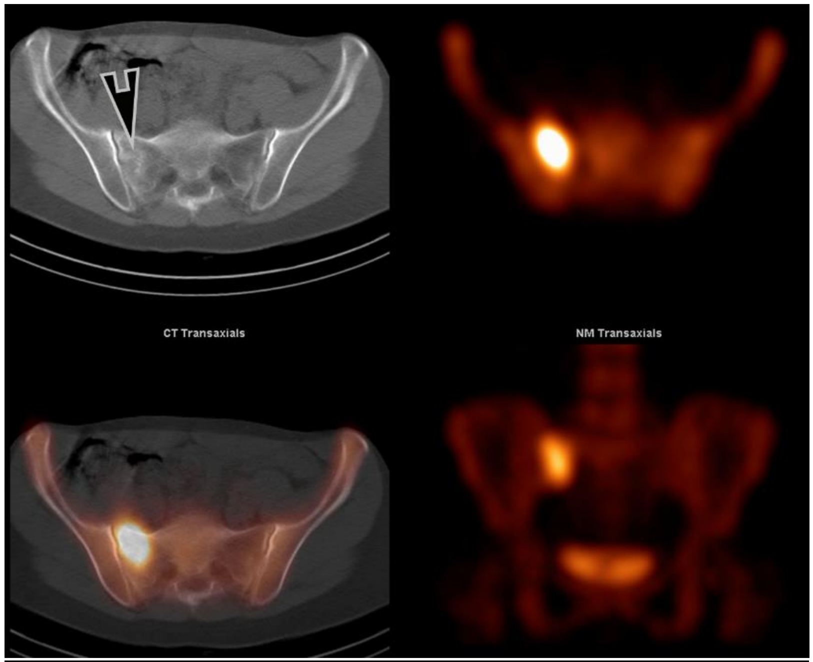


Figure 41. Stress fracture of right sacral ala. The SPECT/CT images show intense increase in uptake of tracer in a vertical pattern extending through the right sacral ala. The CT study shows subtle sclerosis at the site of fracture (arrowhead). The patient was a 38-year-old female long-distance runner who presented with increasingly severe right buttock pain while running.

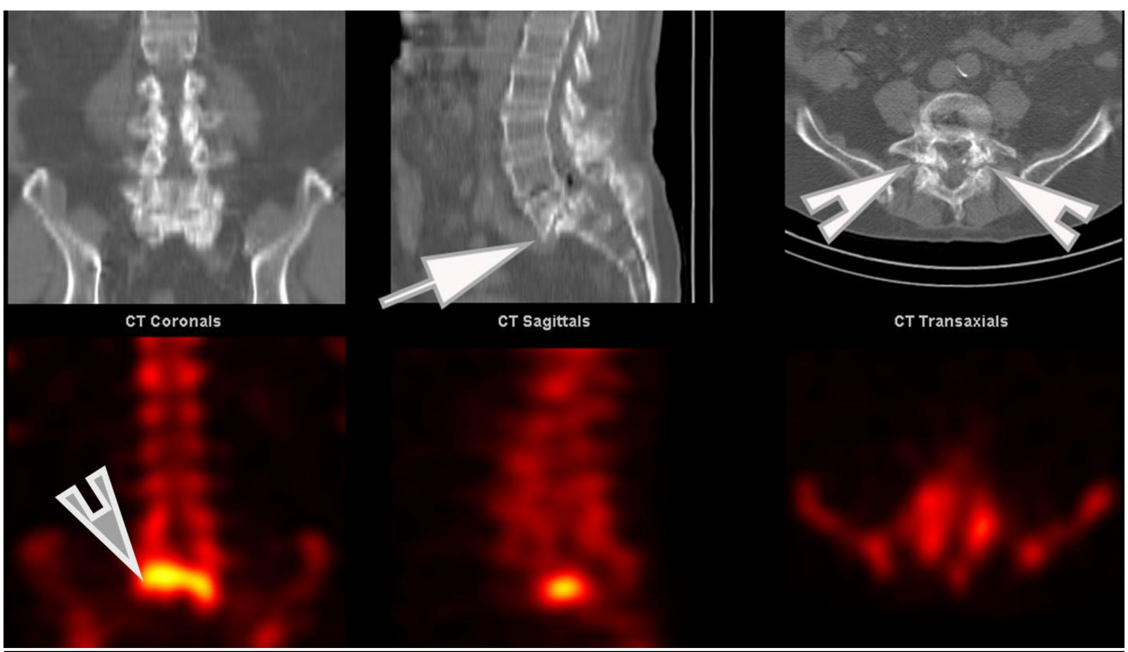


Figure 42. SPECT/CT of spondylolisthesis in a veteran long-distance runner. The patient had established pars fractures of L5 with a manageable level of back pain which significantly worsened after tripping. The study demonstrates chronic pars fractures of L5 with significant sclerosis around the fracture lines (arrowheads) and anterolisthesis of L5 on S1 (arrow). It is likely that the tripping further worsened the anterolisthesis, hence the intense uptake around the compromised intervertebral disc as well (arrowhead in the coronal SPECT image).

Stress fractures of the pubic rami have also been reported in runners and in Australian Rules football participants[72]. Stress fractures of the inferior pubic rami have been reported in military recruits, runners (Figure 43) and triathletes[73]. The mechanism has been purported to be repetitive force transferred through muscle contraction of the adductor magnus, brevis, gracilis and obturator internus and externus to the pubic rami.[73] It often presents as groin pain and should be considered together with femoral fracture (Figure 39), osteitis pubis, adductor enthesopathy, femero-acetabular hip impingement (Figure 7) and inguinal hernias.

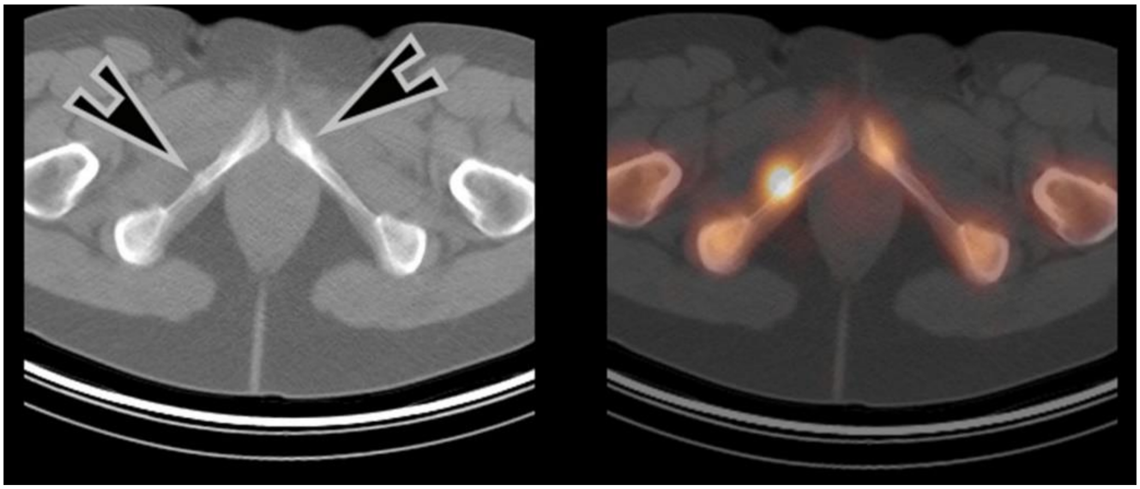


Figure 43. Stress fractures of the inferior pubic rami. The SPECT/CT images show intense focal uptake of tracer in the right pubic ramus with less intense uptake on the left side. The CT study demonstrates sclerotic changes at both sites (arrowheads). The patient was a female long-distance runner.

UNUSUAL CONDITIONS

Other unusual conditions that may lead to diagnostic confusion in athletes include non-traumatic synovitis of the second metatarsophalangeal (MTP) joint[74]. This presents with an identical pattern of symptoms as metatarsal fractures and is easily recognised on MRI and bone scintigraphy with SPECT/CT imaging (Figure 44). The aetiology remains obscure but may be related to the biomechanics of the second metatarsal bone.

Stress fractures have also been reported in the ribs (Figure 45) in rowing, pitching or throwing, basketball, weightlifting, golf, gymnastics and swimming[75]. The mechanism of the injury is thought to be due to overuse of the serratus anterior and external oblique muscles on the ribs in the action of rowing, throwing, pitching and weight lifting.

Figure 44. Synovitis of the second MTP joint. The fused SPECT/CT images show intense uptake in a periarticular pattern around the second MTP joint of the left foot. The pathophysiology is thought to be related to the biomechanics of the second metatarsal bone.

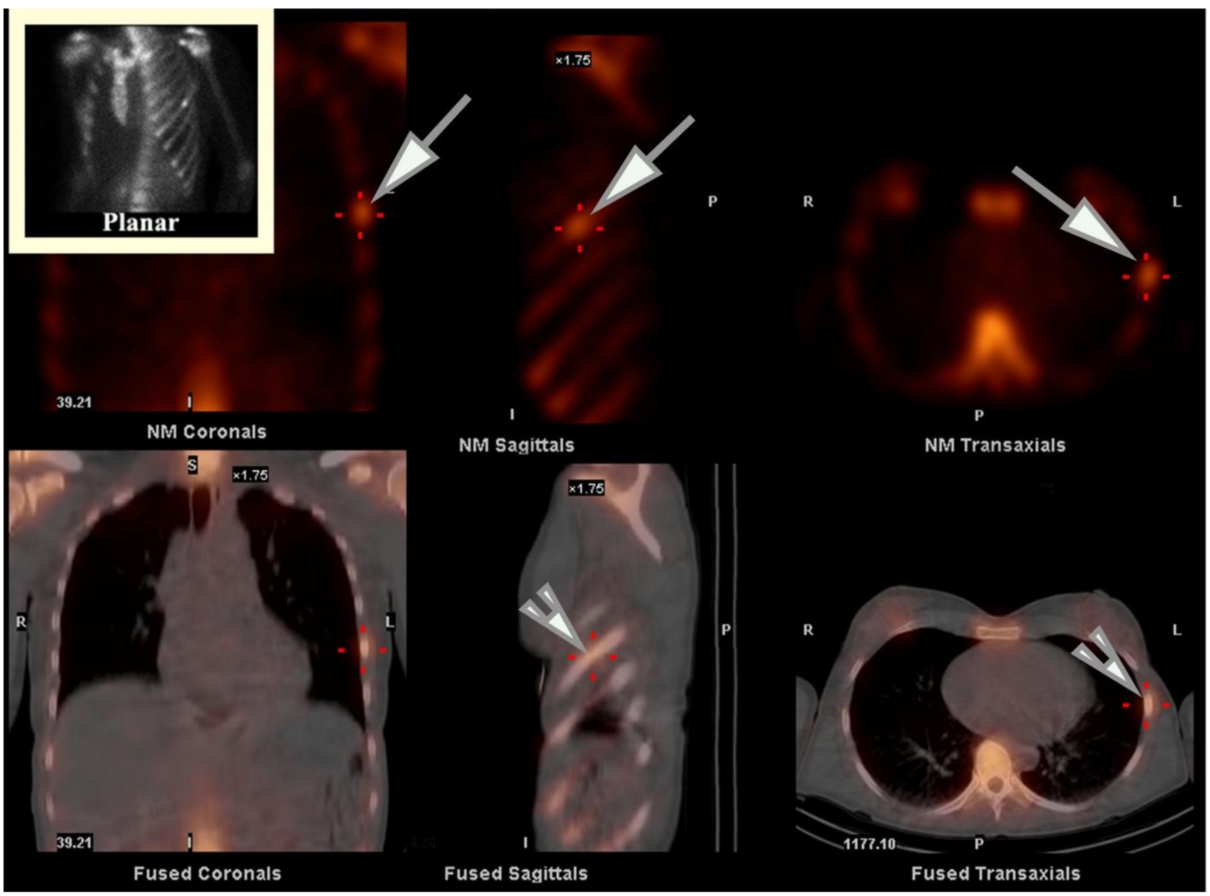


Figure 45. Stress fracture of a left-sided rib in a rower. The patient had presented with increasingly severe pain around the left axilla. Plain films had been reported as normal and the patient was referred for bone scintigraphy. The inset delayed planar image demonstrates focal increase in uptake of tracer in the anterolateral aspect of the left sixth rib with the SPECT/CT images confirming focal uptake (arrows) and cortical thickening without a clear-cut lucent fracture line (arrowheads) in the CT study.

Conclusion

Advances in imaging technology have significantly improved the accuracy and specificity of scintigraphic bone imaging with the development of hybrid instruments capable of SPECT/ CT, allowing registration and fusion of the sensitive functional scintigraphic images with the high spatial resolution of x-ray computed tomography. Advances in the resolution recovery of the scintigraphic instruments have further enhanced the utility of scintigraphic imaging. While MRI and high-resolution ultrasound imaging have supplanted many of the earlier uses of scintigraphic imaging, an emerging role for fusion imaging with SPECT/CT has significantly helped in the acute setting in complex anatomical regions such as the wrist, cervical spine and ankle by significantly increasing the conspicuity of subtle CT scan changes by co-registration with the high sensitivity of scintigraphy. It has also allowed the development of imaging of significant soft tissue abnormalities of the tendons, ligaments and muscles in areas where MRI has shown little utility. The greatest utility of scintigraphic imaging remains the early detection of repetitive stress injuries, often at a preclinical stage, allowing early intervention and prevention of more catastrophic results with progression to cortical disruption.

Conflicts of Interest Statement:

None of the authors have any conflicts of interest to declare

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