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Research Article

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Osteonecrosis of the Lesser Metatarsal Heads

N K Sferopoulos

Department of Pediatric Orthopaedics, 'G. Gennimatas' Hospital, Thessaloniki, Greece

***Corresponding author**

N K Sferopoulos, Department of Pediatric Orthopaedics, G. Gennimatas Hospital, Thessaloniki, Greece.

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Abstract

Osteonecrosis of the lesser metatarsal heads may be detected in both children and adults. It is also defined as Freiberg's disease. It is an uncommon syndrome whose etiology combines potential developmental anomalies, biomechanical stresses or traumatic events, subchondral fracture and vascular injury. The second metatarsal head is the most commonly involved. The disease is much more common in females and athletes. The diagnosis is based on the clinical findings and is confirmed with plain radiographs. On physical examination, the palpable swelling, the discomfort and the motion restriction are well localized at the affected metatarsophalangeal joint. The history may be one of exacerbations and remissions, with pain aggravated by activity and relieved by rest. However, in a group of patients the disorder escapes diagnosis, until the foot is radiographically examined for a totally different reason. Radiographically, the metatarsal head may have a flattened, enlarged appearance with areas of increased sclerosis, fragmentation and collapse, resulting in incongruity of the joint surface. In the long-standing disease, the affected metatarsophalangeal joint may be narrowed and prominent secondary degenerative changes may be evident. The goal of treatment is early identification and conservative treatment of the patient, to allow bone healing and prevent rapid progression to osteoarthritis. No operative treatment modalities are effective in the early stages but surgical intervention is usually required in the late stages of the disease. The purpose of this editorial is to retrospectively review the incidence of osteonecrosis of the lesser metatarsal heads in children and adults referred at our institution and to review the relevant publications.

Keywords: Freiberg's disease, Lesser metatarsal heads, Osteonecrosis, Osteochondrosis.

Editorial

Osteochondrosis of a metatarsal head in children is an articular and growth cartilage disorder of the epiphyseal nucleus leading to osteonecrosis. While the term osteochondrosis may be used only in the premature skeleton, the terms osteonecrosis, avascular, aseptic or ischemic metatarsal head necrosis may be used in both children and adults. Whenever the lesion is localized to the lesser metatarsal heads it is defined as Freiberg's disease. The term osteochondrosis is preferred than that of osteochondritis, which more specifically refers to infection or inflammation of bone and cartilage in children. Osteochondrosis may be either in the primary deformans or in the dissecans form. The former affects the entire primary ossification center and is divided in non-articular traction (pulling), articular subchondral (crushing) and physeal osteochondroses. The latter affects a more limited bone and cartilage portion of weight-bearing areas in older children and is defined as articular chondral (splitting) osteochondrosis. The pathological origin of articular subchondral (crushing) osteochondrosis, including Perthes, Kienböck, Köhler and Freiberg disease, occurs in three stages. In the first stage, the intra- and peri-articular soft tissues are swollen and engorged. In the second stage, there is an irregularity of the epiphyseal contour. In the last stage, the necrotic bone is replaced [1, 2]. On the contrary, Weinstein indicates that the origin of Freiberg's disease is thought to be similar to that of osteochondritis dissecans of the knee [3].

Pedal osteochondroses may cause pain and/or limping in children. They may be localized anywhere in the pediatric foot involving the calcaneal apophysis (Sever's disease), the talus, the tarsal navicular (Köhler's disease), the cuboid, the cuneiform bones, the apophysis of the fifth metatarsal base (Iselin's disease), the metatarsal heads, typically the second metatarsal head (Freiberg's disease or Köhler's disease II), the accessory ossicles and sesamoids, and the phalangeal epiphyses. Osteonecrosis of the first metatarsal head has very rarely been detected in children. It is most commonly reported in adults as a consequence of hallux valgus surgical correction. Unlike the first metatarsal, reports of iatrogenic osteonecrosis after surgical intervention to the lesser metatarsals are scarce [4-27].

Osteochondrosis of the second metatarsal head was initially described by A. Freiberg in 1914, in a series of 6 patients, and then by A. Köhler in 1923 [28-33]. It is occasionally defined as

Freiberg's infarction, while it is also called Freiberg's infraction. Infarction would suggest a vascular event leading to osteonecrosis. The term infraction was the one used by Freiberg to indicate an incomplete fracture of the metatarsal head without displacement of the fragments [34].

Freiberg's disease is the only osteochondrosis that is more common in females. The incidence rate in females is approximately 5:1 relative to males. There is no side dominance with typically only one lesion found per foot. Bilateral involvement is reported in less than 10% of cases. Although osteochondrosis can affect all metatarsal heads, 68% of cases relate to the second metatarsal head, whereas 27% occur in the third and 3% in the fourth. The disease occurs in adolescence, before the epiphyseal closure of the metatarsal head has been completed. The peak age of presentation is between 11 and 17 years but the disease can affect women up to their seventh decade. Several mechanisms have been proposed for its pathogenesis. Osteonecrosis is thought to be secondary to microfractures from repetitive stress overloading or acute trauma. However, it is most likely a multifactorial disorder and several other contributing etiologic factors, such as vascular compromise, rapid growth, genetic and hormonal factors and a skeletal maturation process, may also be involved. Predisposing conditions for osteonecrosis, especially in adults, may include corticosteroid administration, excessive alcohol intake and other systemic disorders, such as diabetes mellitus, systemic lupus erythematous and hypercoagulability. With a reasonable extraosseous and intraosseous blood supply present, physical stresses or trauma seem to bear more influence on the development of Freiberg's disease. With an increase in involvement in sports activities by children and adolescents, recently, there has been a concomitant increase in both acute and overuse injuries. The disease may sometimes be seen with an accompanying stress fracture of the metatarsal shaft. The second metatarsal is typically the longest and the most rigid, resulting in that the head may experience the greatest amount of stress in weight bearing and toe-off. That could cause repetitive microfractures, loss of blood supply to the subchondral bone, collapse of this cancellous bone and cartilage deformation, creating a dorsal-distal lesion on the metatarsal head. It is possible that Freiberg's disease in adults has the same pathogenesis. In many adult cases, a long standing hallux valgus deformity may cause the transfer of weight away from the first metatarsal to the second metatarsophalangeal (MTP) joint, resulting in exacerbated stresses. This side-effect may also follow all osteotomies and fusions used in hallux valgus correction, since they are almost all associated with a varying degree of shortening of the first ray. On the other hand, distal osteotomies in conjunction with lateral soft tissue release were also reported to have an up to 40% risk of osteonecrosis, due to vascular damage [3, 22, 35-49]. The results of pathology of a resected second metatarsal head in a patient with Freiberg's disease, indicating no evidence of necrotic bone, suggested the possibility that in adults the disorder may be in fact the result of a shearing-compression type of injury occurring at the interface between mineralized and nonmineralized articular cartilage. An anatomical examination of MTP joints in cadavers showed that during walking at the toe-off position, the toes raise to force the metatarsal head into plantar flexion. The proximal phalanges ride dorsally over the metatarsal heads producing an externally applied shearing force to them [50].

Patients usually present with pain, tenderness and swelling localized to the involved metatarsal head region of the forefoot. The onset of symptoms is typically gradual, with no specific acute event. Synovitis and pain are usually secondary to the presence of a flap of loose articular cartilage or osteochondral fragment similar to osteochondritis dissecans in the knee or ankle [51]. Pain may be elicited on passive range of motion. Motion may be limited and painful. Patients may complain of stiffness and may walk with a limp secondary to the pain. They may occasionally describe the sensation that they are walking on something hard, such as a stone. The symptoms are worse with barefoot walking and when shoes with high heels or flexible soles are used. Freiberg's disease may severely affect patients in regards to the quality of life and their level of activities, especially due to the young age of the onset of symptoms. On physical examination, the affected toe may have a swollen appearance, especially near the MTP joint. Elevation (dorsiflexion) of the toe may be present. In the more chronic or advanced stages, sagittal or coronal plane malalignment may develop, such as hammertoes or crossover deformities. The range of motion at the MTP joint is reduced and crepitation may be palpated. At the plantar fat pad, a callus may develop under the involved metatarsal head. Digital Lachman testing can be performed, which evaluates joint instability and is graded based on the amount of dorsal translation of the proximal phalanx relative to the metatarsal head, and compared to the contralateral foot. The test is abnormal with dorsal joint subluxation, which will typically reproduce the patient's pain [22, 52].

The standard radiographic evaluation of Freiberg's disease includes anteroposterior and lateral weight-bearing and oblique lateral images of the forefoot. On plain foot radiographs, there may be subtle changes early in the disease presentation, characterized by joint space widening due to effusion, which may last for approximately 3 to 6 weeks following the onset of symptoms. As the disease process progresses, there is increased bone density at the subchondral region and flattening of the metatarsal head. Oblique radiographs of the forefoot assist in the evaluation of the dorsal aspect of the metatarsal head, allowing the identification of flattening of the metatarsal head in subtle cases. As the disease progresses, later findings include central joint depression, loose bodies, and sclerosis of the metatarsal head. There may be reactive thickening of the metatarsal shaft as a late response due to abnormal bone stresses. The final stages of the disease include joint space narrowing and prominent osteoarthritic changes. Magnetic resonance imaging (MRI) may assist in the early detection of Freiberg's disease when radiographs are normal. The MRI will reflect synovitis and changes in the marrow signal with an edema-like signal localized to the affected metatarsal head. As the process progresses, changes similar to osteonecrosis occur. These changes include a hypointense signal on T1-weighted images and mixed hypointense and hyperintense signals on T2-weighted images with flattening of the affected metatarsal head, best appreciated on the sagittal images. MRI is also useful in determining the extent of the lesion when planning surgical correction. Nuclear medicine bone scans may also be used in the evaluation of these patients in the setting of early presentation or if there are no appreciable changes on radiographs. Early changes on bone scan include a photopenic area surrounded by increased radiotracer uptake, the typical pattern for early avascular necrosis. In later stages, diffuse hyperactivity may be

evident, secondary to revascularization, osseous repair, and progression to arthritic involvement of the MTP joint [32, 52-57].

The natural history of Freiberg's disease is variable. In many cases, the condition is self-limited with revascularization of the affected metatarsal head. Early physeal closure may occur [58]. Many patients have no pain or discomfort and good range of motion. In these cases diagnosis may be an incidental finding. However, in most cases the disease course involves exacerbations and remissions. The disease process may leave the metatarsal head enlarged and deformed. A prominent ridge at the dorsal aspect of the metatarsal shaft may be palpated. There is also some painless limitation of flexion and extension. Sometimes, and if no proper prophylactic measures are taken, metatarsalgia caused by the bony enlargement may supervene. Later on, when the patient is 40-50 years old, the joint becomes fixed in a manner analogous to hallux rigidus and secondary degenerative changes may occur at the MTP joint [51, 59].

Although the structural changes to the metatarsal head have classically been described intraoperatively, these same findings are evident radiographically and have also been adapted on a nonoperative basis. The pathological process begins on the dorsal surface of the metatarsal head. It involves evolution in five stages including a subchondral narrow fissure fracture in the ischemic epiphysis with sclerotic cancellous bone surrounding the fracture (stage 1), absorption of the cancellous bone in the center of the metatarsal head, leading to collapse of the subchondral bone, while the margins of the plantar aspect of the metatarsal head remain intact (stage 2), further central bony resorption, creating larger projections on either side (stage 3), fracture of the plantar hinge, after the central portion of the articular surface has sunk deep enough, while peripheral projections have fractures to form loose bodies, indicating that restoration of the normal anatomy is no longer possible (stage 4) and, finally, arthrosis with flattening and deformity of the metatarsal head, while the metatarsal shaft is thickened and dense (stage 5) [39, 60, 61].

Figure 1: Dorsal-plantar radiograph of a 14-year-old girl indicating unilateral osteochondrosis involving the second right metatarsal head. A stage 3 lesion, according to Smillie's classification, with metatarsal head collapse, flattening, sclerosis, irregularity and joint widening, was evident.

Figure 2: Dorsal-plantar radiograph of a 14-year-old girl indicating unilateral osteochondrosis involving the second left metatarsal head. A stage 3 lesion, according to Smillie's classification, with cartilaginous tearing and detachment of a separated bone fragment associated with central metatarsal head resorption, flattening, sclerosis, irregularity and joint widening, was diagnosed. She participated in karate training since 3 years ago. She reported that metatarsalgia and local edema appeared 6 months earlier.

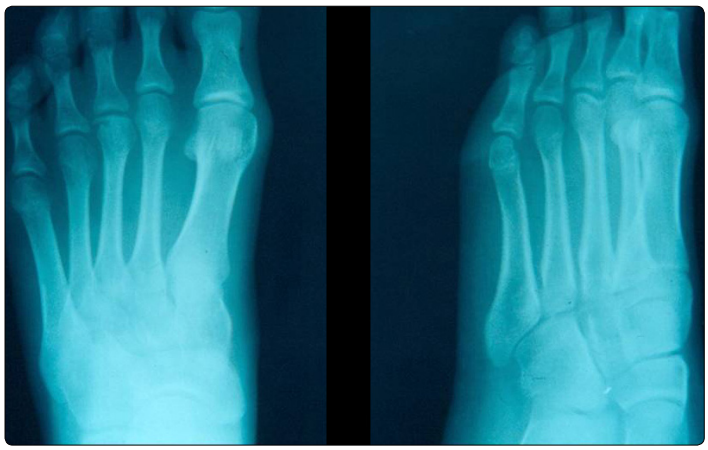

Figure 3: Dorsal-plantar and oblique radiographs of a 13-year-old female indicating unilateral osteochondrosis involving the third left metatarsal. A stage II lesion, according to Smillie's classification, with cartilaginous tearing, detachment of a separated bone fragment and collapse of the subchondral bone, while the margins of the plantar aspect of the metatarsal head were intact, was diagnosed.

Figure 4: Oblique and dorsal-plantar radiographs of a 32-year-old female indicating unilateral osteonecrosis involving the second right metatarsal head. A stage 4 lesion, according to Smillie's classification, with metatarsal head flattening, sclerosis, irregularity, joint widening and spurring, was diagnosed.

Figure 5: Oblique and dorsal-plantar radiographs of a 29-year-old female indicating unilateral osteonecrosis involving the fourth left metatarsal head. A stage 4 lesion, according to Smillie's classification, with metatarsal head flattening, sclerosis, irregularity, joint widening and spurring, was diagnosed.

The differential diagnosis of disorders producing discomfort in the metatarsal region of the forefoot includes traumatic lesions of the soft tissues and bones (turf toe, plantar plate disruption with adjacent pseudoneuroma, sesamoiditis and stress reaction or fracture), Freiberg's disease, infection, inflammatory arthritis (rheumatoid or gouty arthritis), tendon disorders (tendinosis, tenosynovitis, tendon rupture), nonneoplastic soft tissue masses (ganglia, bursitis, granuloma, interdigital Morton neuroma), and, less frequently, soft tissue or bone neoplasms. The classic finding of flattening of the metatarsal head on plain films will confirm the clinical suspicion. However, the lesion is difficult to diagnose in its early stages and scintigraphy or MRI may be needed to distinguish it from a march or fatigue (stress) fracture of the metatarsal neck or shaft [52, 62-65].

Initial treatment should be conservative. Symptomatic treatment is thought to be adequate in most early cases. It includes decreasing activities and rest. In patients who have more acute symptoms, a short-leg walking cast with a toe extension may provide relief. Crutches may occasionally be used to rest the painful foot completely. Once the acute symptoms have subsided, the use of metatarsal pads inserted in the shoe or metatarsal bars on the sole of the shoe may provide comfort and support. These two measures are designed to allow for weight bearing on the metatarsal neck as opposed to the metatarsal head in order to decrease the stresses applied to the metatarsal head. A custom-made foot orthosis designed to provide pressure relief over the metatarsal head may be used on a long-term basis once the acute symptoms have subsided, in patients with mild symptoms or after surgical treatment. Most patients with early changes respond to conservative treatment and obtain satisfactory long-term results. Spontaneous healing with remodeling of the necrotic bone and restoration of joint congruity may occur in the early stages of the disease (stages 1, 2 and 3) [22, 32, 59-62, 66-73].

A large number of surgical procedures have been proposed for the treatment of osteonecrosis of the lesser metatarsal heads when conservative measures have failed. If the symptoms persist and the joint is free of degenerative changes removal of the necrotic fragment alone may provide symptomatic relief. However, most techniques attempt to salvage the situation in patients with late stages of the disease. The painful degenerated disease of the second MTP joint is frequently progressive and difficult to treat. There is little consensus among surgeons as to which procedure should be primarily performed. A number of surgical techniques may be offered, while the most popular ones involve i) osteotomy through the neck, which is the treatment of choice in the typical symptomatic adolescent case, ii) debridement, synovectomy and removal of the loose bodies, iii) metatarsal shortening osteotomy of approximately 4 mm in length, iv) resection of the base of the proximal phalanx and v) resection of the metatarsal head [39, 51, 74-77].

The surgical options in the treatment of osteonecrosis of the metatarsal head are generally divided into two categories, focusing on either altering the abnormal physiology and biomechanics of the metatarsal or at restoring the articular congruency and the arthritic sequelae encountered in the later stages of the disease [78-80]. The former may include subchondral drilling and microfracture, as marrow stimulation techniques, and core decompression techniques to promote revascularization of the necrotic bone. The latter may include open or arthroscopic joint debridement, synovectomy and remodeling of the metatarsal head, elevation of the depressed articular fragment associated with bone grafting harvested from just above the medial malleolus,

intra- or extra-articular (head or neck) dorsal closing-wedge metatarsal osteotomies, shortening osteotomy of the distal shaft, osteochondral plug transplantation or osteochondral distal metatarsal allograft reconstruction, joint distraction arthroplasty, soft tissue interpositional arthroplasty, resection arthroplasty (metatarsal head or phalangeal base with syndactylization of the second and third toe to avoid significant shortening) and implant arthroplasty [51, 81-122].

Outcomes of nonoperative and operative management are generally good to excellent. When surgery is warranted, it is imperative the patient's age, activity level and degree of articular deformity be taken into account [123]. The timing of surgery may also be vital since there may be a crucial period in the progression of the disease when surgery would be more likely to be successful [41]. Complete resolution of pain and return to full activity was reported in 90% of the performed surgeries [59]. However, little is known about the long-term outcome of patients irrespective of method of treatment. The wide variety of operative techniques may indicate that the results of the various treatment options have been unsatisfactory. The results of joint destructive procedures are less favorable in comparison with joint-preserving procedures. Complete resolution of pain and full return to activities is described in approximately 70% of the joint destructive procedures, whereas after joint-preserving procedures this was achieved in more than 90% of cases. The most commonly reported complications of the surgical techniques include persistent pain, joint stiffness, floating toes, transfer metatarsalgia, weak dorsiflexion, hardware irritation and a painful scar [124, 125]. Resection arthroplasty is suggested for advanced cases of Freiberg's disease. However, this technique may be complicated by metatarsal shortening and cosmetic problems. Since Freiberg's disease is more common in young women, cosmetic concerns are highly valued. Excision of the metatarsal head, including an approximately 5 mm removal of the articular surface, should be reserved for patients with impaired joint congruency and severe cartilage damage. Extensive metatarsal head excision is usually complicated by secondary or iatrogenic brachymetatarsia. For diagnostic purposes, brachymetatarsia is defined as shortening of the metatarsal superior to 5 mm. It is usually followed by metatarsalgia due to excessive loading of the adjacent metatarsals and stretching of the transverse metatarsal ligament. This leads to the formation of intractable plantar keratosis that may be very painful for the patient and is difficult to treat. Consequently, removal of the metatarsal head is not recently recommended [51, 126-132].

The radiographs of children and adults with foot injuries or disorders that were referred to both the emergency and the outpatient department between January 2000 and December 2005 were retrospectively evaluated by the author from the hospital radiographic database. From a total amount of approximately 1.200 children and 600 adults, 11 patients with radiographic findings consistent with osteonecrosis of the metatarsal heads were identified. There were 7 children up to 14 years of age (average 13.5 years) and 4 adults (average 30 years). The most commonly affected site was the second metatarsal head, which was involved in 8 patients, while the third and the fourth were involved in two and one patient, respectively. The lesion involved only females and was unilateral in all cases.

A primary diagnosis of a metatarsal head lesion was made in 10 of the patients. Pain, both at rest and after standing or walking, was the predominant clinical feature, although the patients also complained of local swelling, tenderness and motion restriction. The radiographic appearance was typical of Freiberg's disease in all cases. According to Smillie's classification, there were 4 children with a type 3 lesion and 3 with a type 2 lesion. In the primarily diagnosed adults (3 patients), all cases were type 4 lesions (Figure 1, 2, 3, 4, 5). All patients were offered symptomatic conservative treatment with satisfactory results.

An adult patient presented with metatarsalgia and a floating toe due to metatarsal shortening, secondary to an extensive metatarsal head excision, performed elsewhere. The resection arthroplasty had been used to treat a stage 3 lesion, according to Smillie's classification, of the third metatarsal head, 7 years ago (Figure 6). It may be prudent to consider that the removed portion of the metatarsal in the performed resection arthroplasty exceeded the required standards, as they are defined in the literature. The diagnosed secondary, iatrogenic, brachymetatarsia was treated conservatively. The patient reported a short-term improvement of the clinical symptoms and signs in daily life activities with appropriate footwear and obtaining supportive treatments.

Unfortunately, all these patients were lost to follow-up and their long-term outcome is not available.

Figure 6: Dorsal-plantar radiograph of a 30-year-old female who was diagnosed with osteonecrosis of the third right metatarsal head. A stage 3 lesion, according to Smillie's classification, with central metatarsal head resorption, flattening, sclerosis, irregularity and joint widening, was evident (a). She was treated with resection of the metatarsal head. Dorsal-plantar radiograph indicating severe secondary brachymetatarsia of the third ray 7 years postoperatively (b).

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References

1. Omer GE Jr (1981) Primary articular osteochondroses. Clin Orthop Relat Res 158: 33-40.
2. Pappas AM (1981) Osteochondrosis dissecans. Clin Orthop Relat Res 158: 59-69.
3. Weinstein SL (2005) The pediatric foot. In: Weinstein SL, Buckwalter JA, eds. Turek's orthopaedics: Principles and their application. 6th ed. Philadelphia: Lippincott Williams & Wilkins.
4. Renander A (1924) Two cases of typical osteochondropathy of the medial sesamoid bone of the first metatarsal. Acta Radiol 3: 521-527.
5. Wagner A (1930) Isolated aseptic necrosis in the epiphysis of the first metatarsal bone. Acta Radiol 11: 80-88.
6. Ilfeld FW, Rosen V (1972) Osteochondritis of the first metatarsal sesamoid: report of three cases. Clin Orthop Relat Res 85: 38-41.
7. Kliman ME, Gross AE, Pritzker KP, Greyson ND (1983) Osteochondritis of the hallux sesamoid bones. Foot Ankle 3: 220-223.
8. Irvin CM, Witt CS, Zielsdorf LM (1985) Post-traumatic osteochondritis of the lateral sesamoid in active adolescents. J Foot Surg 24: 219-221.
9. Ogata K, Sugioka Y, Urano Y, Chikama H (1986) Idiopathic osteonecrosis of the first metatarsal sesamoid. Skeletal Radiol 15: 141-145.
10. Keating S, Fisher D, Keating D (1987) Avascular necrosis of an accessory sesamoid of the foot. A case report. J Am Podiatr Med Assoc 77: 612-615.
11. Fu FH, Gomez W (1989) Bilateral avascular necrosis of the first metatarsal head in adolescence. A case report. Clin Orthop Relat Res 246: 282-284.
12. Bayliss NC, Klenerman L (1989) Avascular necrosis of lesser metatarsal heads following forefoot surgery. Foot Ankle 10: 124-128.
13. Banks AS (1999) Avascular necrosis of the first metatarsal head. A different perspective. J Am Podiatr Med Assoc 89: 441-453.
14. Easley ME, Kelly IP (2000) Avascular necrosis of the hallux metatarsal head. Foot Ankle Clin 5: 591-608.
15. Toussirot E, Jeunet L, Michel F, Kantelip B, Wendling D (2003) Avascular necrosis of the hallucal sesamoids update with reference to two case-reports. Joint Bone Spine 70: 307-309.
16. Suzuki J, Tanaka Y, Omokawa S, Takaoka T, Takakura Y (2003) Idiopathic osteonecrosis of the first metatarsal head: a case report. Clin Orthop Relat Res 415: 239-243.
17. Edwards WH (2005) Avascular necrosis of the first metatarsal head. Foot Ankle Clin 10: 117-127.
18. Kraft D, Zippin J (2007) Pediatric problems and rehabilitation geared to the young athlete. In: Porter D, Schon L, eds. Baxter's the foot and ankle in sport. 2nd ed. Philadelphia: Mosby Elsevier.
19. DiGiovanni CW, Patel A, Calfee R, Nickisch F (2007) Osteonecrosis in the foot. J Am Acad Orthop Surg 15: 208-217.
20. Garrido IM, Bosch MN, González MS, Carsí VV (2008) Osteochondritis of the hallux sesamoid bones. Foot Ankle Surg 14: 175-179.
21. Gillespie H (2010) Osteochondroses and apophyseal injuries of the foot in the young athlete. Curr Sports Med Rep 9: 265-268.
22. Cerrato RA (2011) Freiberg's disease. Foot Ankle Clin 16: 647-658.
23. Arbab D, Wingenfeld C, Rath B, Lüring C, Quack V, Tingart M (2013) Osteochondrosis of the pediatric foot. Orthopade 42: 20-29.
24. Kwon YU, Choi JS, Kong GM, Ha BH (2017) Idiopathic avascular necrosis of first metatarsal head in a pediatric patient. J Foot Ankle Surg 56: 683-686.
25. Moon DK (2019) Epidemiology, cause, and anatomy of osteonecrosis of the foot and ankle. In: Hunt KJ, ed. Avascular necrosis of the foot and ankle. Foot and Ankle Clinics 24: 1-16.
26. Sferopoulos NK (2019) Tarsal navicular osteonecrosis in children. Int J Ortho Res 2: 1-5.
27. Sferopoulos NK (2019) Juvenile osteochondrosis of the cuneiform bones. Clin Res Pediatr 2: 1-4.
28. Freiberg AH (1914) Infraction of the second metatarsal-a typical injury. Transactions of the Southern Surgical and Gynecological Association 26: 171-174.
29. Freiberg AH (1914) Infraction of the second metatarsal bone. Surg. Gynecol. Obstet 19: 191-193.
30. Köhler A (1923) Typical disease of the second metatarsophalangeal joint. Am J Roentgenol 10: 705-710.
31. Freiberg AH (1926) The so-called infraction of the second metatarsal bone. J Bone Joint Surg 8: 257-261.
32. Hoskinson J (1974) Freiberg's disease: review of long-term results. Proc R Soc Med 67: 10.
33. Ficat RP, Arlet J (1980) Ischemia and necrosis of bone. Baltimore: Williams & Wilkins.

34. Rodrigo RM, Vilanova JC, Ereño MJ, Santisteban JM (2014) Overuse injuries. In: Rodrigo RM, Vilanova JC, José Martel J, eds. Sports injuries in children and adolescents. Berlin Heidelberg: Springer-Verlag.

35. Johnson H (1953) Osteochondritis of the second metatarsal head; Freiberg's infraction. J Natl Assoc Chirop 43: 39-40.

36. Braddock GT (1959) Experimental epiphysial injury and Freiberg's disease. J Bone Joint Surg Br 41: 154-159.

37. Crock HV (1967) The blood supply of the lower limb bones in man. Edinburgh London: Livingstone Ltd.

38. Ary KR Jr, Turnbo M (1979) Freiberg's infraction: an osteochondritis of the metatarsal head. J Am Podiatry Assoc 69: 131-132.

39. Gauthier G, Elbaz R (1979) Freiberg's infraction: a subchondral bone fatigue fracture. A new surgical treatment. Clin Orthop Relat Res 142: 93-95.

40. Walsh HP, Dorgan JC (1988) Etiology of Freiberg's disease:? Trauma. J Foot Surg 27: 243-244.

41. Smith TWD, Kreibich DN (1988) Freiberg's disease. In: Hetherington, VJ, ed. Hallux valgus and forefoot surgery. New York: Churchill Livingstone.

42. Stanley D, Betts RP, Rowley DI, Smith TW (1990) Assessment of etiologic factors in the development of Freiberg's disease. J Foot Surg 29: 444-447.

43. Betts RP, Stanley D, Smith TWD (1991) Foot pressure studies in Freiberg's disease. Foot 1: 21-27.

44. Nguyen VD, Keh RA, Daehler RW (1991) Freiberg's disease in diabetes mellitus. Skeletal Radiol 20: 425-428.

45. Viladot A Sr, Viladot A Jr (1991) Osteochondroses: Aseptic necrosis of the foot. In: Jahss MH, ed. Disorders of the foot and ankle. 2nd ed. 3rd vol. Philadelphia: WB Saunders.

46. Petersen WJ, Lankes JM, Paulsen F, Hassenpflug J (2002) The arterial supply of the lesser metatarsal heads: a vascular injection study in human cadavers. Foot Ankle Int 23: 491-495.

47. Salvi AE, Metelli GP (2004) A case of Freiberg's disease in an adult patient. Chir Organi Mov 89: 325-328.

48. Blitz NM, Yu JH (2005) Freiberg's infraction in identical twins: a case report. J Foot Ankle Surg 44: 218-221.

49. Pollack D (2019) Freiberg's infraction in a geriatric patient-A case report. Int J Foot Ankle 3: 031

50. Young MC, Fornasier VL, Cameron HU (1987) Osteochondral disruption of the second metatarsal: a variant of Freiberg's infraction? Foot Ankle 8: 103-109.

51. Wülker N, Stephens MM, Cracchiolo A III (1998) An atlas of foot and ankle surgery. St. Louis, Mosby.

52. Carter KR, Dreyer MA (2019) Freiberg infarction. StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing.

53. Mandell GA, Harcke HT (1987) Scintigraphic manifestations of infraction of the second metatarsal (Freiberg's disease). J Nucl Med 28: 249-251.

54. Binek R, Levinsohn EM, Bersani F, Rubenstein H (1988) Freiberg disease complicating unrelated trauma. Orthopedics 11: 753-757.

55. Harilainen A, Kuusela T, Tallroth K (1993) MRI for diagnosis of metatarsal osteonecrosis. A case report. Acta Orthop Scand 64: 112-113.

56. Torriani M, Thomas BJ, Bredella MA, Ouellette H (2008) MRI of metatarsal head subchondral fractures in patients with forefoot pain. AJR Am J Roentgenol 190: 570-575.

57. Bahk YW (2013) Combined scintigraphic and radiographic diagnosis of bone and joint diseases. 4th ed. Berlin Heidelberg: Springer-Verlag.

58. Sedlin ED (1983) Early epiphyseal fusion in Freiberg's infraction. Foot Ankle 3: 297-298.

59. Ombregt L (2013) Disorders of the forefoot and toes. In: Ombregt L. ed. A system of orthopaedic medicine. 3rd ed. Edinburgh: Churchill Livingstone Elsevier.

60. Smillie IS (1967) Treatment of Freiberg's infraction. Proc R Soc Med 60: 29-31.

61. Talusan PG, Diaz-Collado PJ, Reach JS Jr (2014) Freiberg's infraction: diagnosis and treatment. Foot Ankle Spec 7: 52-56.

62. Manusov EG, Lillegard WA, Raspa RF, Epperly TD (1996) Evaluation of pediatric foot problems: Part I. The forefoot and the midfoot. Am Fam Physician 54: 592-606.

63. Ashman CJ, Klecker RJ, Yu JS (2001) Forefoot pain involving the metatarsal region: differential diagnosis with MR imaging. Radiographics 21: 1425-1440.

64. Espinosa N, Maceira E, Myerson MS (2008) Current concept review: metatarsalgia. Foot Ankle Int 29: 871-879.

65. Hodes A, Umans H (2018) Metatarsalgia. Radiol Clin North Am 56: 877-892.

66. Scartozzi G, Schram A, Janigian J (1989) Freiberg's infraction of the second metatarsal head with formation of multiple loose bodies. J Foot Surg 28: 195-199.

67. Beito SB, Lavery LA (1990) Freiberg's disease and dislocation of the second metatarsophalangeal joint: etiology and treatment. Clin Podiatr Med Surg 7: 619-631.

68. Stanley D, Smith TWD, Rowley DI (1991) The conservative and surgical management of Freiberg's disease. Foot 1: 97-100.

69. Katcherian DA (1994) Treatment of Freiberg's disease. Orthop Clin North Am 25: 69-81.

70. Hefti F (1999) Foot-pain. Orthopade 28: 173-179.

71. Air ME, Rietveld AB (2010) Freiberg's disease as a rare cause of limited and painful relevé in dancers. J Dance Med Sci 14: 32-36.

72. Shane A, Reeves C, Wobst G, Thurston P (2013) Second metatarsophalangeal joint pathology and Freiberg disease. Clin Podiatr Med Surg 30: 313-325.

73. Longworth R, Short L, Horwood A (2019) Conservative treatment of Freiberg's infraction using foot orthoses: A tale of two prescriptions presented as a case study to open debate. Foot (Edinb) 41: 59-62.

74. Smillie IS (1957) Freiberg's infraction Köhler's second disease. J Bone Joint Surg Br 39: 580.

75. Giannestras NJ (1973) Foot disorders: Medical and surgical management. 2nd ed. Philadelphia: Lea & Febiger.

76. Trott AW (1982) Developmental disorders. In: Jahss MH, ed. Disorders of the foot. Philadelphia: WB Saunders.

77. Smith TW, Stanley D, Rowley DI (1991) Treatment of Freiberg's disease. A new operative technique. J Bone Joint Surg Br 73: 129-130.

78. Thompson FM, Hamilton WG (1987) Problems of the second metatarsophalangeal joint. Orthopedics 10: 83-89.

79. Carmont MR, Rees RJ, Blundell CM (2009) Current concepts review: Freiberg's disease. Foot Ankle Int 30: 167-176.

80. Schade VL (2015) Surgical management of Freiberg's infraction: A systematic review. Foot Ankle Spec 8: 498-519.

81. Cracchiolo A 3rd, Kitaoka HB, Leventen EO (1988) Silicone implant arthroplasty for second metatarsophalangeal joint disorders with and without hallux valgus deformities. Foot Ankle 9: 10-18.

82. Kanse P, Chen SC (1989) Dorsal closing wedge osteotomy for Freiberg's disease. J Bone Joint Surg Br 71: 889.

83. Kinnard P, Lirette R (1989) Dorsiflexion osteotomy in Freiberg's disease. Foot Ankle 9: 226-231.

84. Kinnard P, Lirette R (1991) Freiberg's disease and dorsiflexion osteotomy. J Bone Joint Surg Br 73: b864-865.

85. Sproul J, Klaaren H, Mannarino F (1993) Surgical treatment of Freiberg's infraction in athletes. Am J Sports Med 21: 381-384.

86. Freiberg AA, Freiberg RA (1995) Core decompression as a novel treatment for early Freiberg's infraction of the second metatarsal head. Orthopedics 18: 1177-1178.

87. Maresca G, Adriani E, Falez F, Mariani PP (1996) Arthroscopic treatment of bilateral Freiberg's infraction. Arthroscopy 12: 103-108.

88. Chao KH, Lee CH, Lin LC (1999) Surgery for symptomatic Freiberg's disease: extraarticular dorsal closing-wedge osteotomy in 13 patients followed for 2-4 years. Acta Orthop Scand 70: 483-486.

89. Palamarchuk HJ, Oehrlein CR (2000) Freiberg's infraction in a collegiate heptathlete. J Am Podiatr Med Assoc 90: 77-80.

90. Hayashi K, Ochi M, Uchio Y, Takao M, Kawasaki K, et al. (2002) A new surgical technique for treating bilateral Freiberg disease. Arthroscopy 18: 660-664.

91. Gong HS, Baek GH, Jung JM, Kim JH, Chung MS (2003) Technique tip: fixation of dorsal wedge osteotomy for Freiberg's disease using bioabsorbable pins. Foot Ankle Int 24: 876-877.

92. Carro LP, Golano P, Fariñas O, Cerezal L, Abad J (2004) Arthroscopic Keller technique for Freiberg disease. Arthroscopy 20 Suppl 2: 60-63.

93. Lin SY, Cheng YM, Huang PJ (2006) Freiberg's infraction-treatment with metatarsal neck dorsal closing wedge osteotomy: report of two cases. Kaohsiung J Med Sci 22(11): 580-585.

94. Lee SK, Chung MS, Baek GH, Oh JH, Lee YH, et al. (2007) Treatment of Freiberg disease with intra-articular dorsal wedge osteotomy and absorbable pin fixation. Foot Ankle Int 28: 43-48.

95. Capar B, Kutluay E, Müjde S (2007) Dorsal closing-wedge osteotomy in the treatment of Freiberg's disease. Acta Orthop Traumatol Turc 41: 136-139.

96. Enríquez Castro JA, Guevara Hernández G, Estévez Díaz G (2008) Interposition arthroplasty as treatment of osteochondritis of the second metatarsal head. A case report. Acta Ortop Mex 22: 259-262.

97. Ozkan Y, Oztürk A, Ozdemir R, Aykut S, Yalçin N (2008) Interpositional arthroplasty with extensor digitorum brevis tendon in Freiberg's disease: a new surgical technique. Foot Ankle Int 29: 488-492.

98. DeVries JG, Amiot RA, Cummings P, Sockrider N (2008) Freiberg's infraction of the second metatarsal treated with autologous osteochondral transplantation and external fixation. J Foot Ankle Surg 47: 565-570.

99. Miyamoto W, Takao M, Uchio Y, Kono T, Ochi M (2008) Late-stage Freiberg disease treated by osteochondral plug transplantation: a case series. Foot Ankle Int 29: 950-955.

100. Edmondson MC, Sherry KR, Afolayan J, Armitage AR, Skyrme AD (2011) Case series of 17 modified Weil's osteotomies for Freiberg's and Köhler's II AVN, with AOFAS scoring pre- and post-operatively. Foot Ankle Surg 17: 19-24.

101. Nagura I, Fujioka H, Kokubu T, Kurosaka M (2011) Autologous osteochondral plug transplantation for osteochondrosis of the second metatarsal head: a case report. J Med Case Rep 5: 308.

102. Lee SK, Kim KJ, Yang DS, Choy WS (2012) Metatarsophalangeal arthroscopic treatment for early stage IV of Freiberg's disease: a case report. Eur J Orthop Surg Traumatol 22 Suppl 1: 233-237.

103. Kim J, Choi WJ, Park YJ, Lee JW (2012) Modified Weil osteotomy for the treatment of Freiberg's disease. Clin Orthop Surg 4: 300-306.

104. Xie X, Shi Z, Gu W (2012) Late-stage Freiberg's disease treated with dorsal wedge osteotomy and joint distraction arthroplasty: technique tip. Foot Ankle Int 33: 1015-1017.

105. Lee HJ, Kim JW, Min WK (2013) Operative treatment of Freiberg disease using extra-articular dorsal closing-wedge osteotomy: technical tip and clinical outcomes in 13 patients. Foot Ankle Int 34: 111-116.

106. Erdil M, Imren Y, Bilsel K, Erzincanli A, Bülbül M, et al. (2013) Joint debridement and metatarsal remodeling in Freiberg's infraction. J Am Podiatr Med Assoc 103: 185-190.

107. Kilic A, Cepni KS, Aybar A, Polat H, May C, et al. (2013) A comperative study between two different surgical techniques in the treatment of late-stage Freiberg's disease. Foot Ankle Surg 19: 234-238.

108. Ajis A, Seybold JD, Myerson MS (2013) Osteochondral distal metatarsal allograft reconstruction: a case series and surgical technique. Foot Ankle Int 34: 1158-1167.

109. Ikoma K, Maki M, Kido M, Imai K, Arai Y, et al. (2014) Extra-articular dorsal closing-wedge osteotomy to treat late-stage Freiberg disease using polyblend sutures: technical tips and clinical results. Int Orthop 38: 1401-1405.

110. Liao CY, Lin AC, Lin CY, Chao TK, Lu TC, et al. (2015) Interpositional arthroplasty with palmaris longus tendon graft for osteonecrosis of the second metatarsal head: a case report. J Foot Ankle Surg 54: 237-241.

111. Helix-Giordanino M, Randier E, Frey S, Piclet B, (2015) The French association of foot surgery (AFCP), Treatment of Freiberg's disease by Gauthier's dorsal cuneiform osteotomy: Retrospective study of 30 cases. Orthop Traumatol Surg Res 101: S221-225.

112. Pereira BS, Frada T, Freitas D, Varanda P, Vieira Silva M, et al. (2016) Long-term follow-up of dorsal wedge osteotomy for pediatric Freiberg disease. Foot Ankle Int 37(1): 90-95.

113. Miyamoto W, Takao M, Miki S, Kawano H (2016) Midterm clinical results of osteochondral autograft transplantation for advanced stage Freiberg disease. Int Orthop 40: 959-964.

114. Desai S (2017) Freiberg's infarction treated with metatarsal shortening osteotomy, marrow stimulation, and micronized allograft cartilage matrix: A case report. Foot Ankle Spec 10: 258-262.

115. Ishimatsu T, Yoshimura I, Kanazawa K, Hagio T, Yamamoto T (2017) Return to sporting activity after osteochondral autograft transplantation for Freiberg disease in young athletes. Arch Orthop Trauma Surg 137: 959-965.

116. Biz C, Zornetta A, Fantoni I, Crimì A, Bordignon E, Ruggieri P (2017) Freiberg's infraction: A modified closing wedge osteotomy for an undiagnosed case. Int J Surg Case Rep 38: 8-12.

117. Daoudi A, Abbassi N, Yahyaoui M, Agoumi O, Najib A, et al. (2018) Gauthier's osteotomy and fixation using osteosuture in the treatment of Freiberg's disease. Pan Afr Med J 29: 33.

118. Abdul W, Hickey B, Perera A (2018) Functional outcomes of local pedicle graft interpositional arthroplasty in adults with severe Freiberg's disease. Foot Ankle Int 39: 1290-1300.

119. Georgiannos D, Tsikopoulos K, Kitridis D, Givisis P, Bisbinas I (2019) Osteochondral autologous transplantation versus dorsal closing wedge metatarsal osteotomy for the treatment of Freiberg infraction in athletes: A randomized controlled study with 3-year follow-up. Am J Sports Med 47: 2367-2373.

120. Lui TH, Fan AKH (2019) Arthroscopic dorsal closing-wedge osteotomy of metatarsal head for management of Freiberg infraction. Arthrosc Tech 8: 1289-1293.

121. Kim SJ, Kim YW, Park JH, Kim GL (2020) Comparison of osteochondral autologous transplantation and dorsiflexion closing wedge metatarsal osteotomy for late-stage Freiberg disease in adults. Foot Ankle Int 41: 529-535.

122. Stautberg EF 3rd, Klein SE, McCormick JJ, Salter A, Johnson JE (2020) Outcome of lesser metatarsophalangeal joint interpositional arthroplasty with tendon allograft. Foot Ankle Int 41: 313-319.

123. Wax A, Leland R (2019) Freiberg disease and avascular necrosis of the metatarsal heads. Foot Ankle Clin 24: 69-82.

124. Seybold JD, Zide JR (2018) Treatment of Freiberg disease. Foot Ankle Clin 23: 157-169.

125. Trnka HJ, Lara JS (2019) Freiberg's infraction: Surgical options. Foot Ankle Clin 24: 669-676.

126. Ihedioha U, Sinha S, Campbell AC (2003) Surgery for symptomatic Freiberg's disease: Excision arthroplasty in eight patients. Foot 13: 143-145.

127. Schimizzi A, Brage M (2004) Brachymetatarsia. Foot Ankle Clin 9: 555-570, ix.

128. Lamm BM, Gourdine Shaw MC (2010) Problems, obstacles, and complications of metatarsal lengthening for the treatment of brachymetatarsia. Clin Podiatr Med Surg 27: 561-582.

129. Wingenfeld C, Arbab D, Abbara Czardybon M (2013) Treatment options for brachymetatarsia. Orthopade 42: 30-37.

130. Özkul E, Gem M, Alemdar C, Arslan H, Boğatekin F, Kişin B (2016) Results of two different surgical techniques in the treatment of advanced-stage Freiberg's disease. Indian J Orthop 50: 70-73.

131. Murphy GA (2017) Lesser toe abnormalities. In: Azar FM, Beaty JH, Canale ST, eds. Campbell's Operative Orthopaedics. 13th ed. Philadelphia: Elsevier.

132. Shecaira AP, Fernandes RMP (2019) Brachymetatarsia: One-stage versus two-stage procedures. Foot Ankle Clin 24: 677-687.