Current Trends in Total Ankle Replacement

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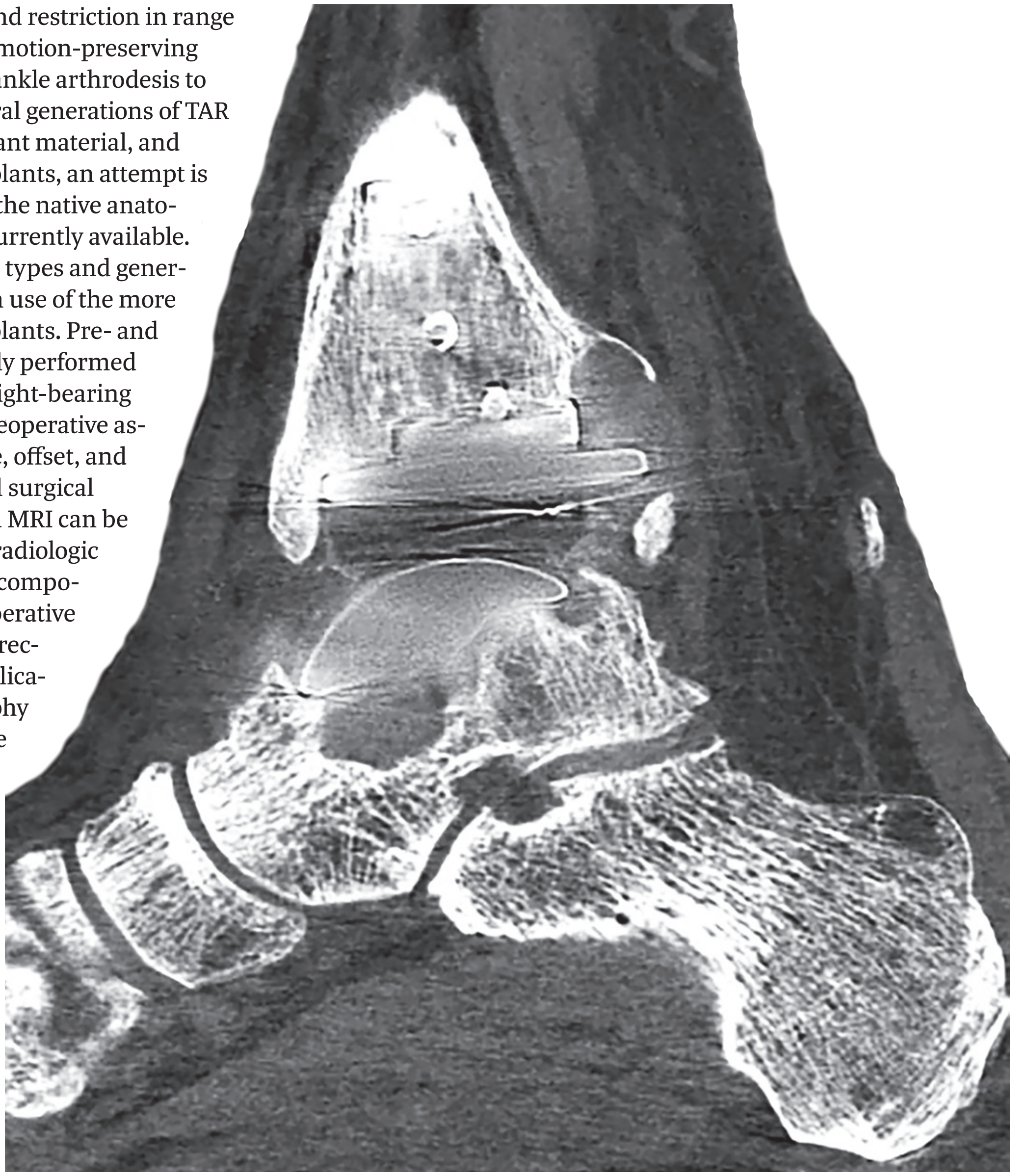
Ankle arthritis can result in significant pain and restriction in range of motion. Total ankle replacement (TAR) is a motion-preserving surgical option used as an alternative to total ankle arthrodesis to treat end-stage ankle arthritis. There are several generations of TAR techniques based on component design, implant material, and surgical technique. With more recent TAR implants, an attempt is made to minimize bone resection and mirror the native anatomy. There are more than 20 implant devices currently available. Implant survivorship varies among prosthesis types and generations, with improved outcomes reported with use of the more recent third- and fourth-generation ankle implants. Pre- and postoperative assessments of TAR are primarily performed by using weight-bearing radiography, with weight-bearing CT emerging as an additional imaging tool. Preoperative assessments include those of the tibiotalar angle, offset, and adjacent areas of arthritis requiring additional surgical procedures. US, nuclear medicine studies, and MRI can be used to troubleshoot complications. Effective radiologic assessment requires an understanding of the component design and corresponding normal perioperative imaging features of ankle implants, as well as recognition of common and device-specific complications. General complications seen at radiography include aseptic loosening, osteolysis, hardware subsidence, periprosthetic fracture, infection, gutter impingement, heterotopic ossification, and syndesmotic nonunion. The authors review several recent generations of TAR implants commonly used in the United States, normal pre- and postoperative imaging assessment, and imaging complications of TAR. Indications for advanced imaging of TAR are also reviewed.



Introduction

Approximately 1% of the world population has painful ankle osteoarthritis, with the majority of cases (90%) being posttraumatic (1,2). Total ankle replacement (TAR) was introduced in the 1970s by Lord and Marotte as a motion-sparing alternative to total ankle arthrodesis for patients with primary osteoarthritis, posttraumatic arthritis, or inflammatory arthritis (3,4). These implants were highly constrained or minimally constrained in design (4,5). Thus, first-generation TAR implants were wrought with high complication rates and poor implant survivorship beyond 2 years (1,6,7).

Second-generation TAR implants were smaller and cemented, allowing less bone resection. These were semiconstrained devices with either mobile or fixed polyethylene liners. In the United States, fixed bearings were preferred for greater stability and lower risk of liner dislocation. Despite

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Abbreviations: AP = anteroposterior, STAR = Scandanavian Total Ankle Replacement, TAR = total ankle replacement

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TEACHING POINTS

- The talar tilt angle is measured on AP weight-bearing ankle radiographs. A vertical line is drawn parallel to the anatomic axis of the tibia. A second line is drawn along the talar dome surface. The resulting angle reflects the varus or valgus deformity, also known as the talar tilt angle.
- On lateral weight-bearing radiographs, offset represents the AP distance between the tip of the lateral process of the talus and the longitudinal axis of the tibia.
- High-grade complications (≥50% failure rate) include implant failure, aseptic loosening, periprosthetic osteolysis, and deep infection. Intermediate-grade complications (<50% failure rate) include technical error, subsidence, periprosthetic fracture, and medial gutter impingement. Low-grade complications are rare and include intraoperative fracture and wound healing issues.
- Expansile osteolysis, also known as ballooning osteolysis or periprosthetic cysts, has been reported in up to 15% of TARs and may lead to device instability, periprosthetic fractures, and talar component subsidence.
- Over time, abnormal varus or valgus alignment can result in altered biomechanics, which can lead to stress fractures, deltoid ligament strain, and/or gutter impingement.

these biomechanical advances, 10-year implant survivorship remained marginal at 80% (3). Third- and fourth-generation devices offer advances in surgical technique for improved soft-tissue balancing and contain cross-linked polyethylene (8,9) for fewer wear-related complications (Fig 1). As survivorship has improved with newer-generation implants, studies have demonstrated near-equivalent outcomes with respect to pain relief and improved quality of life between arthroplasty and arthrodesis groups (10,11). Arthroplasty is typically performed instead of arthrodesis in patients who desire a return to an active lifestyle and range of motion at the ankle and do not have contraindications such as neuropathic arthropathy, infection, or inadequate bone stock.

More than 20 different TAR devices are available; however, the second- and third-generation U.S. Food and Drug Administration (FDA)–approved systems commonly used in the United States include the Salto Talaris Anatomic Ankle (Integra LifeSciences), Scandanavian Total Ankle Replacement (STAR) (DJO Global), INBONE II Total Ankle System (Wright Medical), Invision Total Ankle Revision System (Wright Medical), and Trabecular Metal Total Ankle System (Zimmer Biomet). Fourth-generation FDA-approved designs include the INFINITY Total Ankle System (Wright Medical), Cadence Total Ankle System (Integra LifeSciences), Vantage Total Ankle System (Exactech), Apex 3D Total Ankle Replacement System (Paragon 28), Hintermann Series H3 Total Ankle Replacement System (DT MedTech), and Kinos Axiom Total Ankle System (Kinos Medical).

There is continued growth in the use of TAR with newer-generation implants (7). Postoperative evaluation involves combined clinical and imaging assessments. It is imperative that radiologists understand the component design of newer-generation ankle replacement systems and be able to recognize normal pre- and postoperative imaging assessment findings and identify device-specific complications to provide meaningful contributions to patient care. This article is focused on normal and abnormal postoperative imaging findings of TAR, preoperative surgical measurements, and the role of weight-bearing CT. Indications for cross-sectional imaging of TAR are also discussed.

Preoperative Imaging Assessment

Preoperative planning for TAR begins with obtaining the patient's medical history and performing a physical examination to ensure proper patient selection. Absolute contraindications to surgery include infection, a compromised soft-tissue envelope, neuropathic arthropathy, and inadequate bone stock (12).

While the imaging study selected for preoperative planning is surgeon dependent, initial imaging requirements for TAR typically consist of weight-bearing anteroposterior (AP) and lateral radiographs. These images are used to assess joint alignment to plan the tibial and talar component sizes, evaluate prior surgical hardware in the ankle and surrounding structures, assess erosive changes of the tibial plafond, and quantify varus or valgus misalignment (12,13). The talar tilt angle is measured on AP weight-bearing ankle radiographs. A vertical line is drawn parallel to the anatomic axis of the tibia. A second line is drawn along the talar dome surface. The resulting angle reflects the varus or valgus deformity, also known as the talar tilt angle (Fig 2A). Large valgus and varus ankle deformities were previously believed to be contraindications to TAR; however, research has shown them to have no effect on clinical outcomes, complications, or revision surgeries (14). In addition, surgeons now use preoperative imaging measurements to correct for the deformities.

Preoperative radiographs are also helpful in assessing for offset. On lateral weight-bearing radiographs, offset represents the AP distance between the tip of the lateral process of the talus and the longitudinal axis of the tibia (Fig 2B). The Canadian Orthopaedic Foot and Ankle Society end-stage ankle arthritis classification system is another valid tool for grouping patients who are undergoing TAR for end-stage ankle arthritis by identifying additional sites that may require surgical correction (Fig 2C) (15). It is important to identify malleolar dysplasia (resulting from varus ankle alignment), which may require osteotomy; determine the degree of hindfoot degenerative change, which may require arthrodesis; and identify large anteromedial and inferolateral talar and anterior fibular osteophytes that would require surgical resection (13). Another optional preoperative imaging study is whole–lower-extremity weight-bearing radiography. The acquired images are used to assess the mechanical axis and varus or valgus alignment at the knee that may require correction (13).

Although radiography may be sufficient for preoperative planning, the use of weight-bearing CT of the foot and ankle is increasing (15). Compared with preoperative radiography, CT not only enables better evaluation of the surrounding

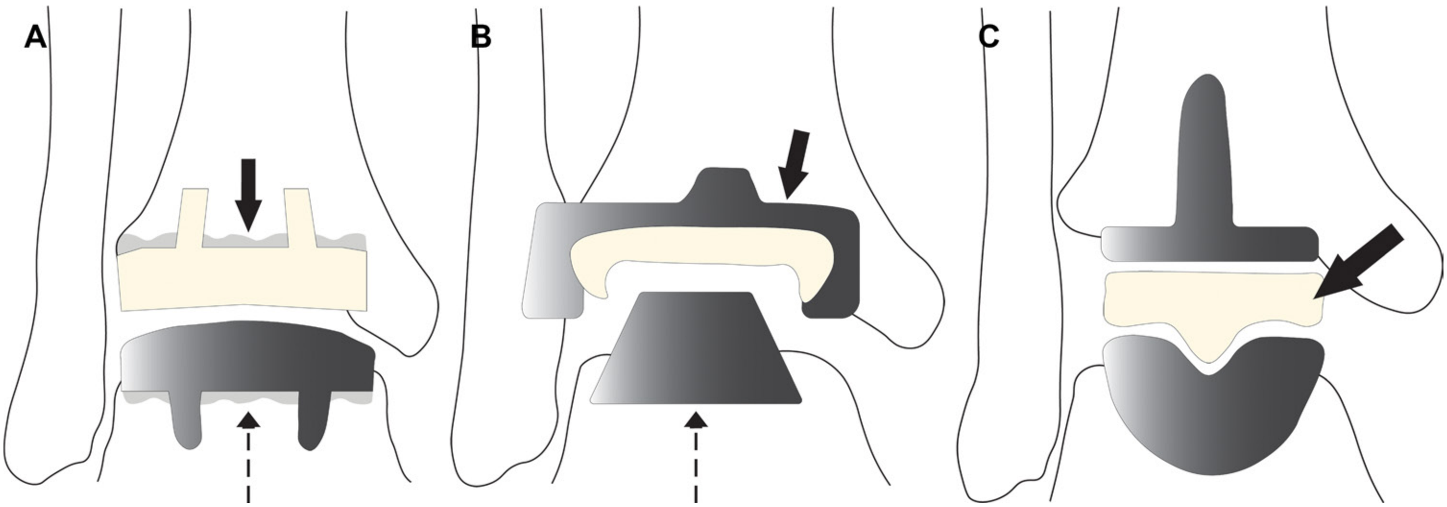
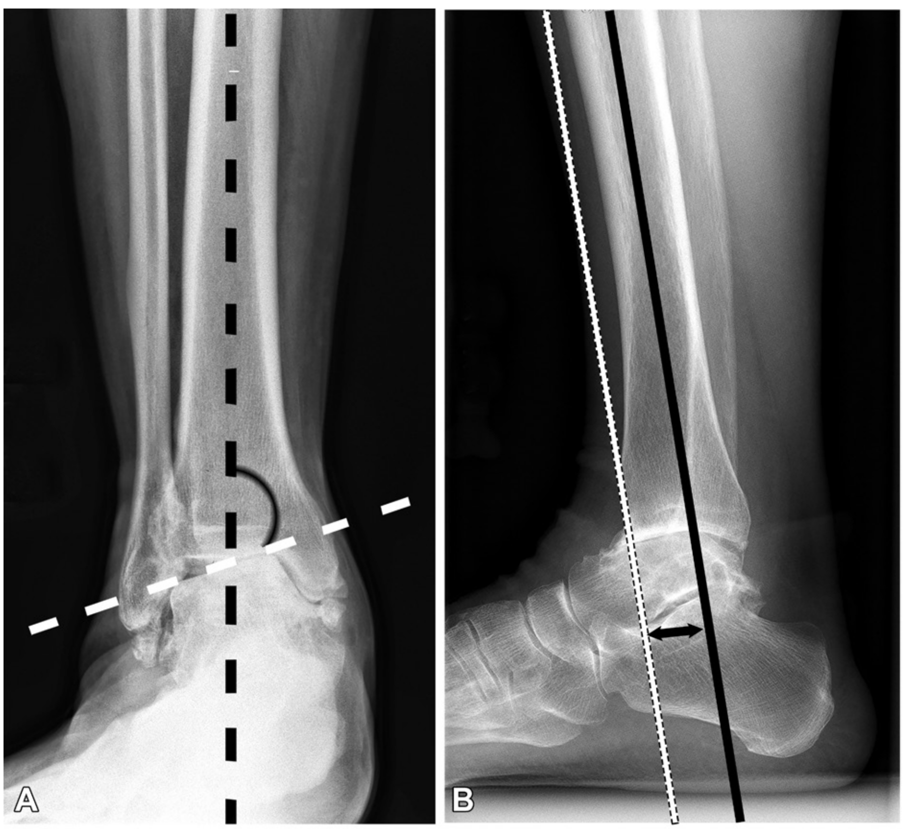


Figure 1. Drawings illustrate the differences between first-generation, fixed-bearing, and mobile-bearing total ankle arthroplasty implants. **(A)** First-generation implants are constrained or semiconstrained two-component devices, typically consisting of a concave polyethylene tibial component and a separate convex metallic talar component. In these devices, cement fixation is used on both the tibial (solid arrow) and talar (dashed arrow) components. **(B)** Fixed-bearing implants are two-component devices in which a polyethylene bearing is fixed to the metallic component on the tibial (solid arrow) or talar (dashed arrow) side. The absence of bone cement allows more conservative bone cuts, and the porous coating on components can precipitate bone ingrowth. **(C)** Mobile-bearing implants are characterized by the presence of a mobile polyethylene bearing (arrow), making these three-component devices. These implants require precise ligament balancing to prevent instability due to the less constrained design.



TYPE 1	TYPE 2	TYPE 3	TYPE 4
Isolated ankle arthritis	Ankle arthritis with varus or valgus deformity (>10 degrees)	Ankle arthritis + hindfoot deformity, tibial malunion, supinated midfoot	Types 1-3 plus subtalar, calcaneocuboid, or talonavicular arthritis

C

Figure 2. Preoperative ankle measurements in two patients. **(A)** AP weight-bearing radiograph in a 54-year-old man shows the talar tilt angle, which reflects the varus or valgus deformity. A vertical line (black dashed line) is drawn along the anatomic axis of the tibia. A second line (white dashed line) is drawn along the talar dome surface. The resulting angle (curved black line) is the talar tilt angle. **(B)** Lateral weight-bearing radiograph in a 49-year-old woman shows the offset, measured as the AP distance (double-headed arrow) between the tip of the lateral process of the talus (white line) and the longitudinal axis of the tibia (black line). **(C)** Chart shows the Canadian Orthopaedic Foot and Ankle Society preoperative system for classifying end-stage ankle arthritis (15).

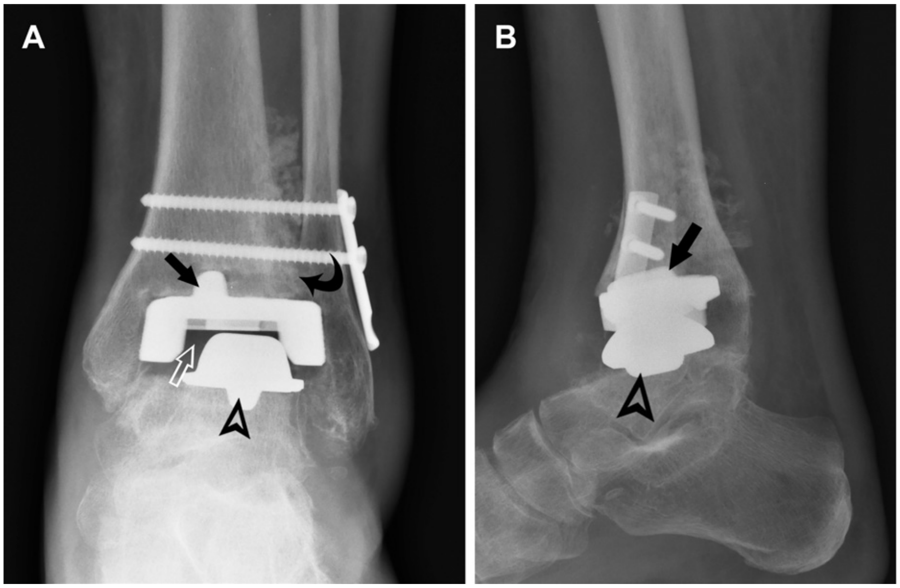


Figure 3. Agility implant in a 67-year-old man. AP **(A)** and lateral **(B)** radiographs show the fixation fins of the titanium tibial (solid straight arrow) and cobalt-chromium talar (arrowhead) components, with a radiolucent polyethylene meniscus (open arrow in **A**) fixed to the tibial component. Fusion of the distal tibiofibular syndesmosis (curved arrow in **A**) stabilizes the tibial component by improving the weight distribution of the prosthesis with fibular load sharing and increased surface area for bone growth.

Figure 4. Agility Total Ankle arthroplasty in a 49-year-old man. AP oblique radiograph 18 months after surgery shows syndesmotic nonunion (arrowheads), which is the most common reason for unsuccessful Agility total ankle arthroplasty. There is also radiolysis (arrow) in the fibula adjacent to the lateral tibial component, a finding associated with poor syndesmotic union.

soft tissues but also helps to more accurately predict the talar component size (16). Furthermore, in postoperative evaluations, specific CT-planned patient guides used before surgery were found to have a greater effect in correcting ankle misalignment and can be used to identify additional diseases, such as adjacent arthritis or hindfoot misalignment, that may require additional concomitant or staged procedures. In addition, weight-bearing CT is now combined with artificial intelligence software for use in surgical planning and/or templating and in selecting patient-specific instrumentation. Consequently, this modality may be indicated for preoperative surgical planning in complicated cases. However, standardized acquisition guidelines and measurement protocols are still needed to ensure reproducibility and optimize the utility of weight-bearing CT.

Implant Devices

Agility Total Ankle Device

The Agility Total Ankle device is a two-piece, fixed-bearing, semiconstrained device used in patients with severe osteoarthritis or rheumatoid arthritis. It is placed by using an anterior surgical approach. This device contains a titanium tibial component, cobalt-chromium talar component, and polyethylene surface of articulation that is designed to replicate tibiotalar anatomic alignment (Fig 3) (17,18). Implant placement is accompanied by tibiofibular syndesmosis fusion to improve the weight-bearing load distribution between the distal tibia and the articulation of the fused tibiofibular surface (18). Since the introduction of the Agility Total Ankle in 1970, several outcome-driven revisions to reduce wear (ie, increasing the size of the tibial component side walls) and ease component revision (ie, designing for a purposeful size mismatch between the tibial and talar components and implementing a 1-mm anterior locking mechanism of the polyethylene) have been made to the device (19). Current use of the device is limited to TAR revisions.

Overall rates of revision for the Agility device vary between 13.5% and 20.0%. The most common causes of revision are talar or tibial subsidence and delayed or failed syndesmotic union of the tibia and fibula (Fig 4) (17,20,21). In the postoperative period, imaging should be used to monitor zones of radiolucency, as opposed to zones of radiolysis, as well as syndesmotic union. Radiolucency (<2 mm) is common in the majority (76%) of patients with implanted Agility devices (22).

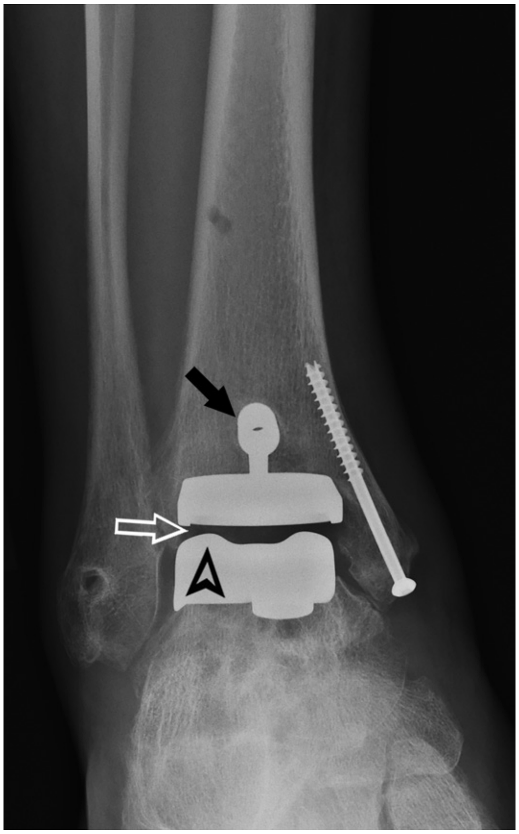


Figure 5. Salto Talaris implant in a 44-year-old man. AP radiograph shows the cobalt-chromium tibial and talar components, including the tapered fixation plug (solid arrow) on the superior aspect of the tibial component that secures the implant against the bone surface. The polyethylene insert (open arrow) is attached to the tibial component. Note the larger lateral radius (arrowhead), as compared with the medial radius, of the talar component, replicating the normal talar anatomy. The screw in the medial malleolus is from a prior traumatic fracture fixation.

Radiolysis (≥2 mm) around the lateral component of the tibial implant has been associated with a poor syndesmotic union (20,22). Furthermore, circumferential radiolucency, radiolysis surrounding the tibial fin, or component migration of greater than 5 mm or 5° has been linked to device failure and revision (23).

Salto Talaris Anatomic Ankle

The Salto Talaris Anatomic Ankle has a fixed-bearing two-component design. It is a fixed-bearing version of the Salto Mobile Prosthesis, which has a three-component mobile design. The Salto Talaris Anatomic Ankle is used in the United States, while the Salto Mobile Prosthesis is used in Europe (24). The components are a titanium-coated cobalt-chromium tibial and talar base, as well as a polyethylene insert attached to the tibial component (Fig 5) (24,25). A tapered fixation plug on the superior aspect of the tibial component secures the implant against the bone surface. The talar component has a larger lateral than medial radius to replicate the normal talar anatomy (25). In one study (26), survivorship, defined according to the incidence of revision surgery, was 97.6% for 85 Salto Talaris implants at 10 years. The most common cause for repeat surgery has been medial or lateral ankle impingement (Fig 6). Other common causes include osteolysis and medial malleolar stress fractures. Common radiographic complications are periprosthetic bone cysts, which are probably due to mechanical stress and release of wear particles from the implant (26).

INBONE I and II Total Ankle Systems

The INBONE I and INBONE II Total Ankle systems are fixed-bearing two-component designs (24,25). The components consist of a titanium-coated cobalt-chromium tibial and talar base, with the tibial component housing the polyethylene bearing (27). The tibial and talar components contain large stems that are intended to decrease the load from the bearing components (24). A longer intramedullary tibial stem can facilitate fixation in poor tibial bone stock. The components are customizable, allowing implant sizing to accommodate patient anatomy (25). The INBONE I implant had a flat talar articulation with the polyethylene component, which contributed to instability. The INBONE II implant has a talar central sulcus that results in a more stable coupling between the talar component and polyethylene insert (Fig 7) (28).

The survivorship at a minimum of 5 years after surgery has been reported to be as high as 98% for 44 INBONE II implants (27). Use of the INBONE II implant, as compared with the INBONE I device, facilitates lower rates of revision for talar subsidence, supporting the efficacy of the improved talar component design (27).

Common radiographically identified complications include periprosthetic bone cysts, particularly at the medial shoulder of the tibial component (27). A unique risk is talar osteonecrosis as a result of drilling near the artery of the sinus tarsi during implantation (Fig 8). In addition, the longer stem, designed to impart lower mechanical load on the implant bearings, results in forces distributed to other sites. This force distribution can contribute to tibial stem fractures, as well as acceleration of prosthesis loosening (25).

INFINITY Total Ankle System

The INFINITY Total Ankle System is a fixed-bearing two-component design (24,25). It is composed of a titanium tibial component and a cobalt-chromium talar component with a polyethylene insert (Fig 9) (24). The three tibial pegs assist in fixation and rotational resistance, while the long tibial tray allows increased cortical coverage. The anterior pegs assist in talar fixation. The INFINITY device is a smaller implant, as compared with previous designs, intended to reduce the quantity of soft-tissue dissection and bone resection during implantation (25). A unique feature of the INFINITY design is that the talar component is interchangeable with the talar component of the INBONE II prosthesis; this is an advantage in the setting of revision surgery. According to a systematic review of six studies involving a total of 432 prostheses (29), the survivorship at a mean follow-up period of 24.5 months was 94% for INFINITY implants. In that review (29), the most

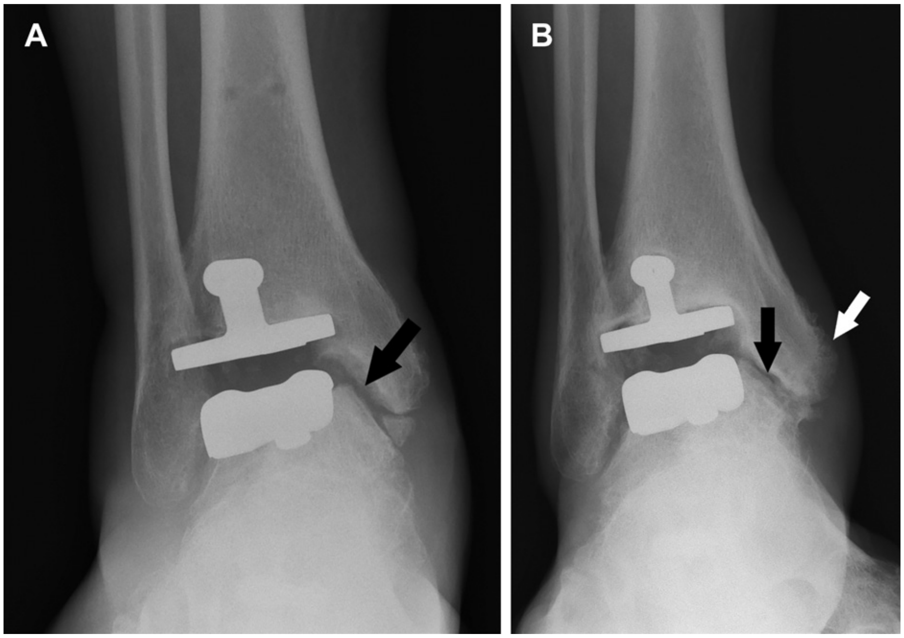


Figure 6. Salto Talaris ankle replacement in a 62-year-old man. **(A)** AP weight-bearing radiograph 1 month after ankle replacement shows a small focus of heterotopic ossification adjacent to the medial malleolus, but the medial tibiotalar joint space (arrow) has been maintained. **(B)** AP weight-bearing radiograph 3 years later shows narrowing of the medial gutter (black arrow) with subchondral sclerosis and periostitis at the medial malleolus (white arrow), consistent with medial gutter impingement. This patient underwent revision to address the symptomatic gutter impingement.

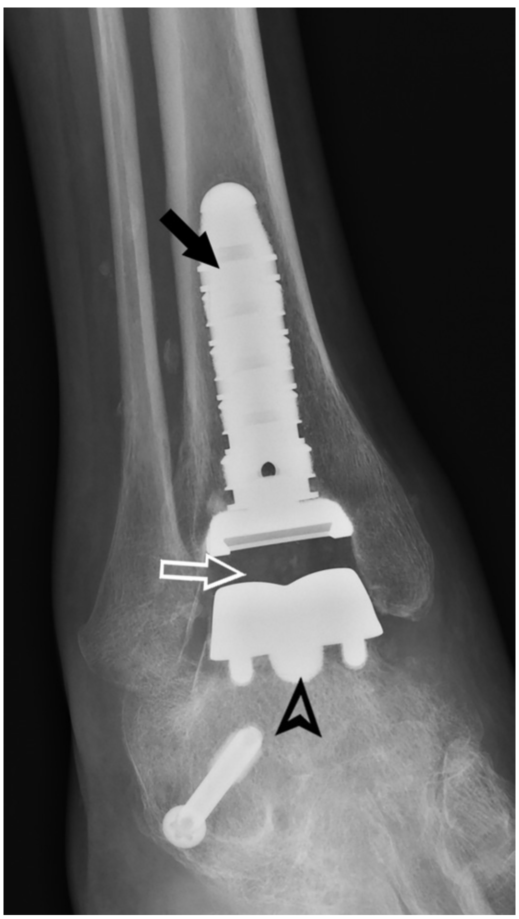


Figure 7. INBONE II implant in a 48-year-old man. AP radiograph shows tibial (solid arrow) and talar (arrowhead) components made of titanium-coated cobalt-chromium. The tibial component houses the polyethylene bearing (open arrow) and has a long intramedullary modular stem, which facilitates better fixation in poor tibial bone stock.

Figure 8. INBONE II implant in a 64-year-old man. Coronal weight-bearing CT image shows diffuse sclerosis and collapse of the talus resulting from osteonecrosis and causing subsidence of the talar component and concomitant lateral impingement with abutment of the distal fibula and lateral talus (arrow).

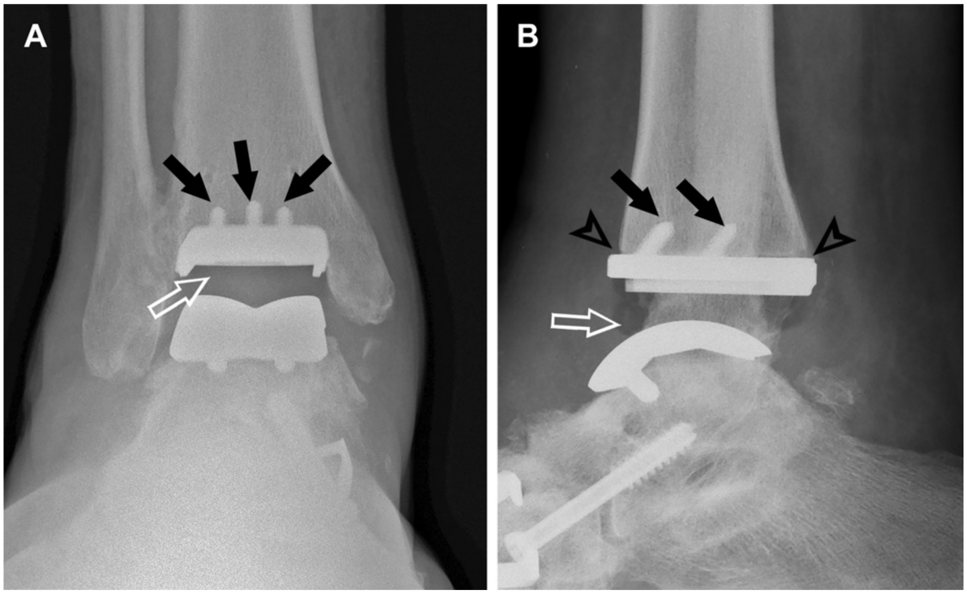


Figure 9. INFINITY implant in a 47-year-old woman. AP **(A)** and lateral **(B)** radiographs show the fixed-bearing design. The tibial pegs (solid arrows) assist in fixation and rotational resistance. The radiolucent polymer (open arrow) is affixed to the tibial tray (arrowheads in **B**), which is longer in the anterior-to-posterior dimension, resulting in increased cortical coverage.

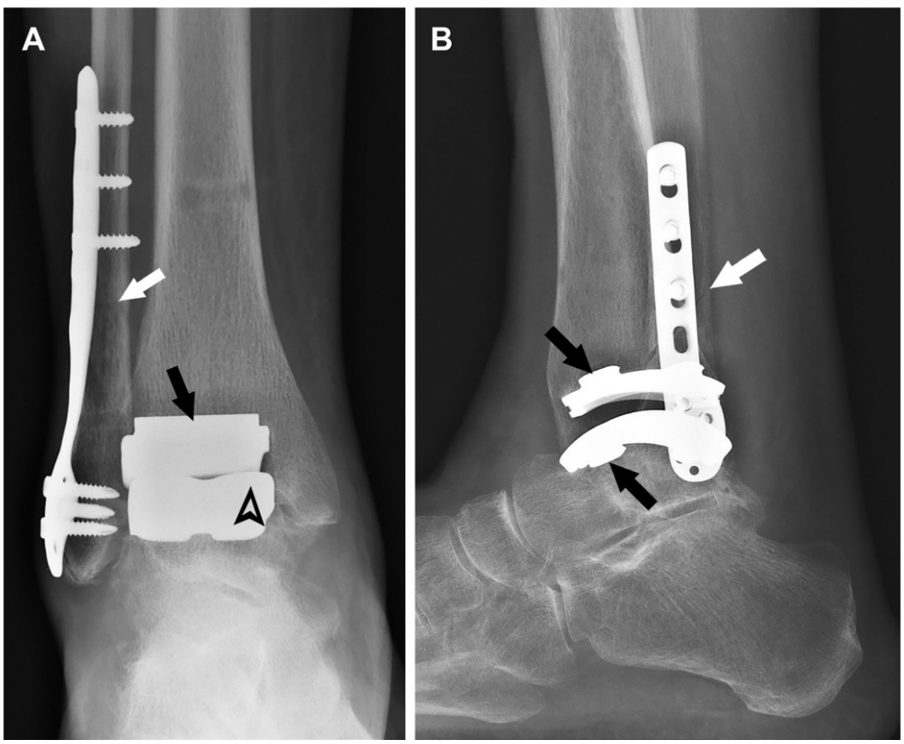


Figure 10. Trabecular Metal Total Ankle implant in a 68-year-old man. AP **(A)** and lateral **(B)** radiographs show an arched tibial and talar articular surface, which approximates the natural bone contour and allows two times the contact area with lower peak pressures. Fixation rails (black arrows) in the coronal plane are designed to counteract shear forces. The medial side of the prosthesis (arrowhead in **A**) has a smaller radius of curvature than the lateral side, decreasing strain on ligament complexes. A lateral approach with transfibular osteotomy (white arrow), as compared with an anterior approach, minimizes wound-healing complications and allows direct visualization of the lateral tibiotalar joint to assess the normal ankle arc of rotation and center of axis.

common radiographically identified complications requiring implant revision were aseptic loosening of the tibial component, subsidence, and postoperative fracture, in addition to the most common clinical complication, deep infection.

Preoperative CT scan–derived patient-specific plans and guides (PROPHECY; Wright Medical) are used for the INBONE and INFINITY prostheses. Studies have shown that use of these patient-specific plans yields accurate and reproducible TAR alignments measured with imaging (30).

Trabecular Metal Total Ankle System

The Trabecular Metal Total Ankle System is a fixed-bearing ankle replacement device composed of a highly cross-linked polyethylene articular surface and a trabecular metal-bearing surface for bone integration (Fig 10) (31,32). Cross-linked polyethylene has demonstrated significantly reduced wear compared with other polymers, while the trabecular (ie, tantalum) metal features an increased coefficient of friction with cancellous bone for improved stability (33,34). For implementation of Trabecular Metal Total Ankle TAR, a lateral transfibular approach unique to TAR is used. This approach is designed to minimize bone resection and provide improved visualization of the joint alignment and angle of rotation for correction of severe deformity (31,35). The surgical approach requires a fibular osteotomy, which offers the advantage of addressing concomitant subtalar arthritis and lateral ankle

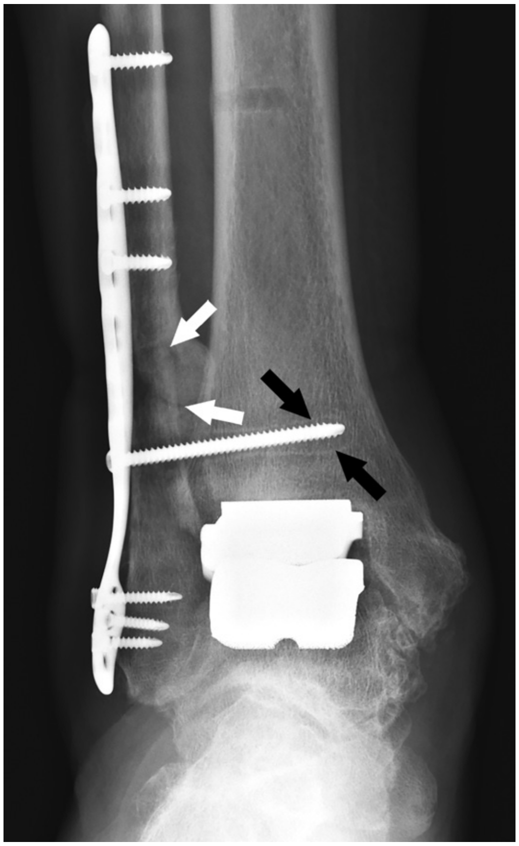


Figure 11. Trabecular Metal Total Ankle TAR in a 48-year-old man. AP radiograph more than 1 year after surgery shows an area of radiolucency larger than 2 mm around the syndesmotic screw (black arrows), indicating hardware loosening and lucent osteotomy margins (white arrows), consistent with nonunion.

disease. For these reasons, it is ideal for patients who have posttraumatic arthritis with a prior lateral incision from fracture repair (32,36).

Clinical follow-up has shown significant increases in function and reduced pain based on scores on the American Orthopaedic Foot and Ankle Society ankle scale, a visual analog scale, and the 12-Item Short Form Health Survey (SF-12) (31,35,37). The increased surgical time with the lateral transfibular approach raised initial concerns regarding infection rate despite avoidance of the neurovasculature potentially being disturbed with an anterior approach. Early studies showed a decrease in both superficial and deep infections with use of Trabecular Metal Total Ankle TAR, as compared with anterior ankle approaches; however, a significant difference was not seen (38). Furthermore, investigation of fibular nonunion and delayed healing has yielded only one study demonstrating that this condition is an indication for revision (35). Common causes of revision surgery include medial and/or lateral gutter pain, pain from hardware, and aseptic loosening of the device (37).

Postoperative examination of patients with Trabecular Metal Total Ankle implants should include weight-bearing AP, lateral, and dorsolateral radiograph acquisitions. Measurements of standard angles for ankle alignment calculated by using the method of Wood and Deakin—the α angle (tibial axis and tibial component in coronal plane), β angle (tibial axis and tibial component in sagittal plane), and γ angle (axis of implant to talar axis in sagittal plane)—have demonstrated long-term stability (39,40). However, evaluation of hindfoot alignment with use of Saltzman view radiographs has facilitated a slight increase in valgus alignment during 2-year follow-up (39). Radiolucency surrounding the anterior portion of the tibia-prosthesis interface is common and does not correlate with pain or poor outcomes (35). In addition, radiolucency may be seen around the rails of the tibial component as a result of intraoperative drilling. Finally, care should be taken to evaluate for fibular union (Fig 11), aseptic loosening (migration of components, excess radiolucency around components, or subchondral cysts), medial tibial stress fracture (Fig 12), and medial and lateral gutter impingement.

Scandinavian Total Ankle Replacement

The STAR system is a mobile-bearing three-component device that has undergone multiple revisions since its initial design in 1978. The fourth-generation model features a noncemented mobile-bearing three-component design and the adoption of a porous titanium coating on the cobalt-chromium bone-implant surface (41). The three-component design allows the metallic components to articulate separately with a mobile ultra–high-molecular-weight polyethylene bearing, or meniscus. Unique features of the STAR system include a radiopaque wire placed within the polyethylene to help with radiographic monitoring (Fig 13). In addition, the flat trapezoid-shaped tibial component houses two cylindric barrels on the implant superiorly, which are used to anchor the device into the subchondral tibia (42). Similarly, the convex talar component has a central fin inferiorly that embeds into the talar surface. The talar component also features a centrally placed talar ridge on the articulation surface, which resists rotational movement and allows only anterior and posterior translation of the meniscus (42,43).

The most frequently reported complications requiring revision are polyethylene fracture and wear, with up to 18% of recorded implants requiring polyethylene bearing replacement (44). Although both polyethylene wear and displacement are potential complications of both fixed- and mobile-bearing devices (Fig 14), they are more commonly observed with three-component devices as a result of two separate polyethylene articulations (42). Also, polyethylene migration may occur in mobile-bearing three-component devices secondary to poor intraoperative ligament balancing, which results in angular instability and excessive joint laxity (42).

Despite complications such as polyethylene displacement, fracture, and wear, which are commonly observed with three-component designs, the fourth-generation STAR system has relatively good survivorship: 89%–96% at 5 years (45,46), 88%–94% at 10 years (41,44), and 73% at 15 years (41).

Vantage Total Ankle System

The Vantage Total Ankle System is a fourth-generation TAR system with both two- and three-component designs (47). In the United States, it is available as a fixed-bearing device with

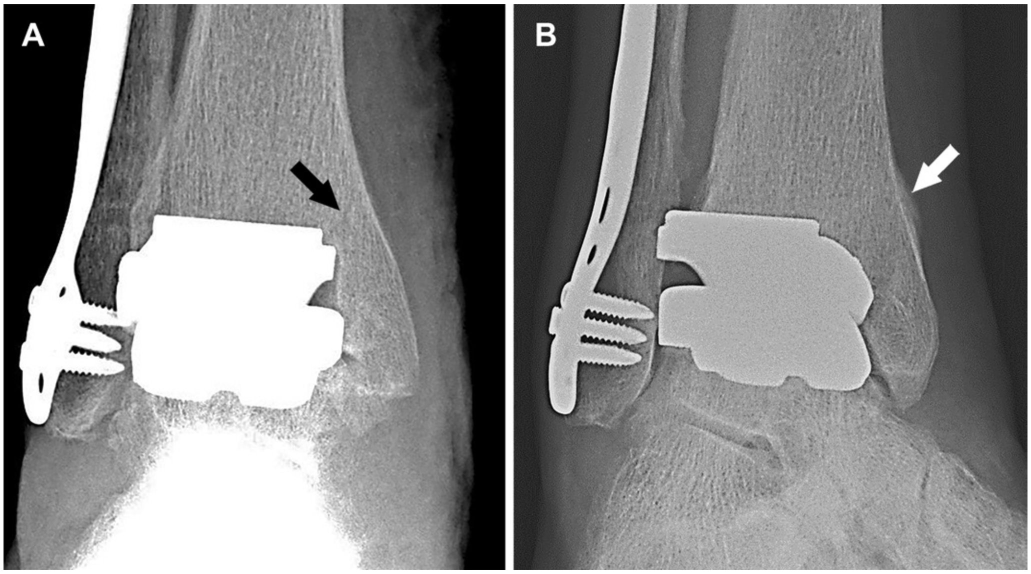


Figure 12. Trabecular Metal Total Ankle TAR in a 62-year-old woman with medial ankle pain. **(A)** AP radiograph shows a lucent fracture line through the medial malleolus (arrow). **(B)** Mortise-view radiograph 2 months later shows periosteal bone formation (arrow), indicating a healing stress fracture. Tibial stress fractures may occur medially with use of the Trabecular Metal Total Ankle design owing to uneven load dispersion on the tibia.

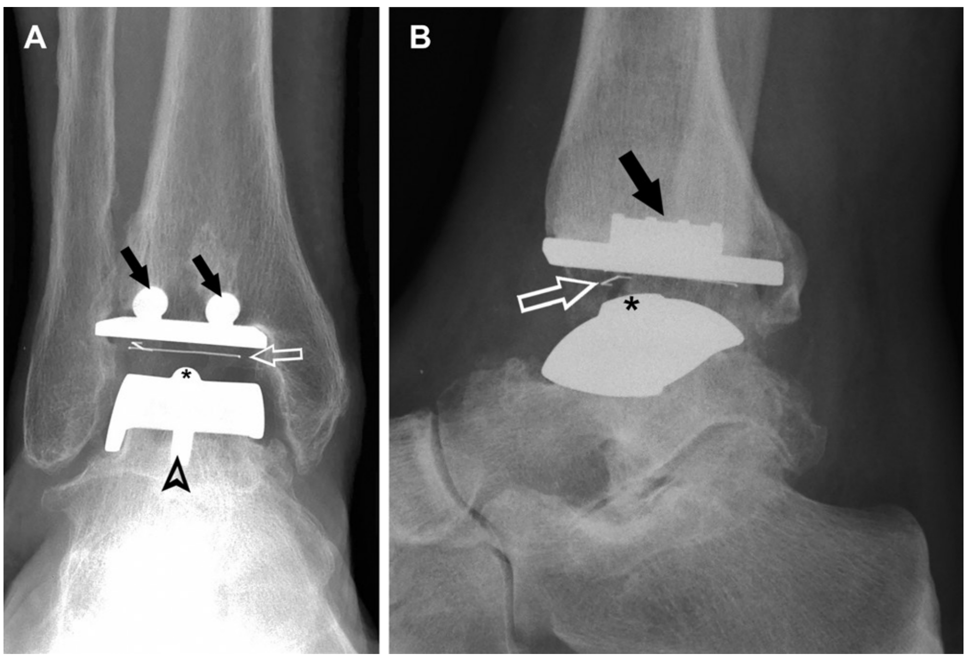


Figure 13. STAR implant in a 65-year-old man. AP **(A)** and lateral **(B)** radiographs show a titanium-coated cobalt-chromium tibial component with cylindric barrels (solid arrows) to anchor the device, and a talar component with a central inferior fin (arrowhead in **A**) embedded into the talus and a ridge on the articulation surface (*) to resist rotational movement. The unconstrained polyethylene meniscus contains a metal wire (open arrow) for radiographic monitoring.

the cross-linked polyethylene spacer clipped into the tibial component (48). The design includes a curved talar component intended to anatomically align with the trabecular bone structure of the talus. Theoretically, this should increase stability and minimize bone resection (Fig 15) (49). An alternate option is a flat cut talus, which provides initial fixation through its press-fit bone cage and plasma pegs. The tibial component includes a groove for fibular articulation (50). Early 2-year outcome reports have included small patient sample sizes but are promising, with complication rates of 4.54% (49) and 6.00% (47). All studies show improvements in mean American Orthopaedic Foot and Ankle Society hindfoot scores, visual analogue scale pain scores, and range of motion measurements. Reported radiographically identified complications include delayed wound healing, tibial cyst formation, and medial malleolus fracture (47,49).

Cadence Total Ankle System

The Cadence Total Ankle System is a fourth-generation two-component fixed-bearing implant. The liner is made of cross-linked polyethylene to reduce wear-related complications. The unique design of the tibial component includes a recess for the fibula to provide three cortices of support and minimize fibular impingement (51). Similar to the talar component of the Vantage Total Ankle System, the Cadence system talar component is designed to minimize bone resection and is anatomically shaped, with a bicondylar talus that has a central trochlear groove. There are also anterior and posterior biased polyethylene liners to address the sagittal plane balance of the ankle (51) and laterality-specific components for the left and right extremities. Early outcome studies showed significant improvement in activity and visual analog scale pain scores with use of this device. Complications

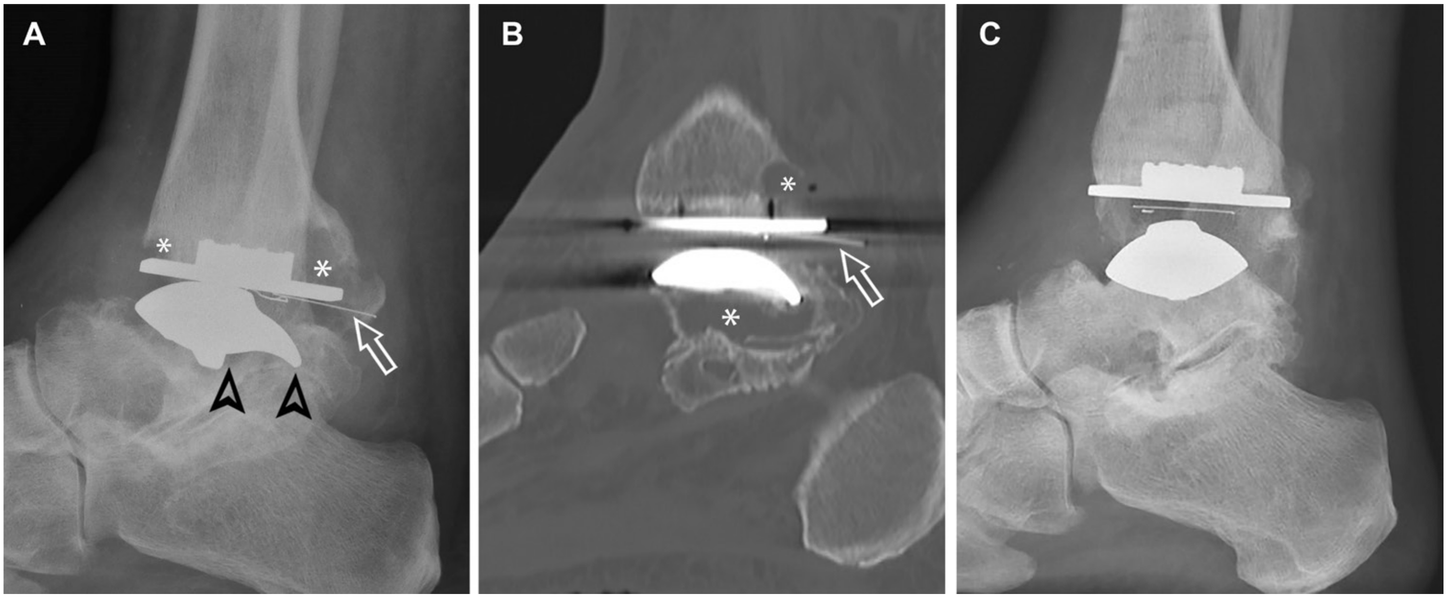


Figure 14. TAR with the STAR system in a 51-year-old man. **(A, B)** Lateral radiographic **(A)** and sagittal CT **(B)** images of the ankle 5 years after TAR show abnormal posterior positioning of the metallic marker inside the radiolucent polymer (arrow), indicating displacement and/or fracture of the polymer. There is osteolysis (∗ in **A** and **B**) about the tibial and talar components and subsidence of the talar component (arrowheads in **A**), which is better appreciated after comparison with the normal initial postoperative radiograph **(C)**.

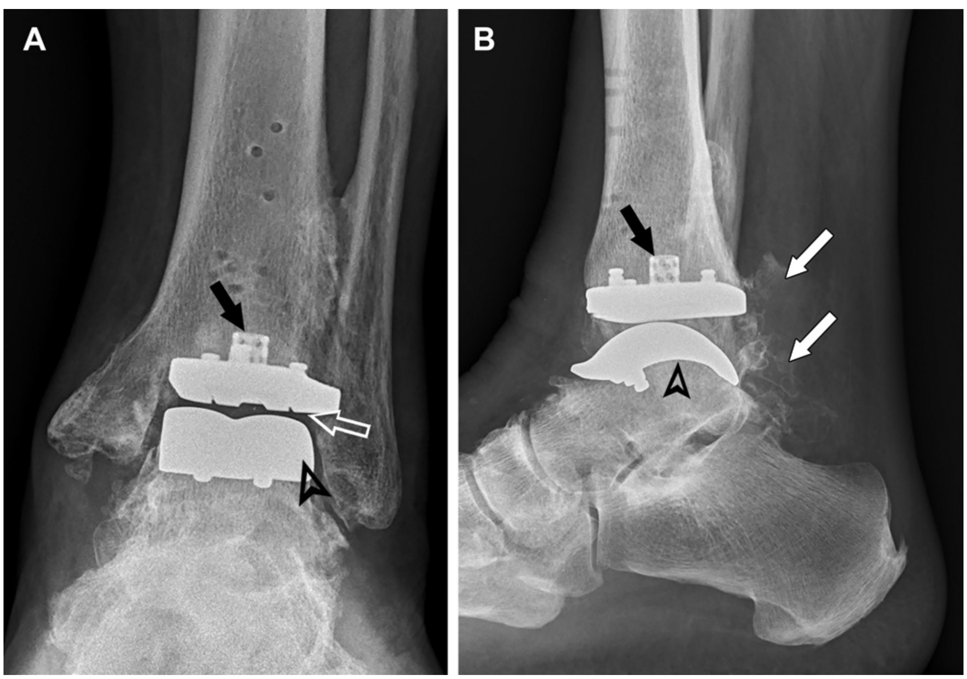


Figure 15. Vantage TAR in a 75-year-old man. AP **(A)** and lateral **(B)** weight-bearing radiographs show the Vantage device, with the talar component (arrowhead) curved to align with the trabecular bone structure of the talus and minimize bone resection. In the fixed-bearing design used in the United States, the polyethylene liner (open arrow in **A**) is clipped into the tibial component (black arrow). Prior ghost holes are noted in the distal tibia diaphysis. There is also heterotopic ossification (white arrows in **B**) posterior to the tibiotalar joint.

include delayed wound healing, periprosthetic fracture, osteolysis, and anterior impingement (52,53).

Immediate Postoperative Imaging

Early postoperative complications include wound-healing issues, infection, fracture, and malalignment (12). It is important to recognize the concomitant procedures performed, such as malleolar, calcaneal, or fibular osteotomy, to prevent misinterpretation as a fracture. Tendoachilles lengthening is sometimes performed to provide adequate dorsiflexion of the replaced ankle and should not be confused with tendon tear. Other sites of ligamentous reconstruction or tendon transfer should be known to identify expected areas of postoperative change. Immediate postoperative imaging should include assessment of alignment. The tibiotalar angle should be less than 10°. It is measured between the long axis of the tibia and a line perpendicular to the talar dome. The anterior distal tibial angle on a lateral radiograph should be within 3° of 89° (12). It is important to note these angles on the first postoperative images to assess for change over time.

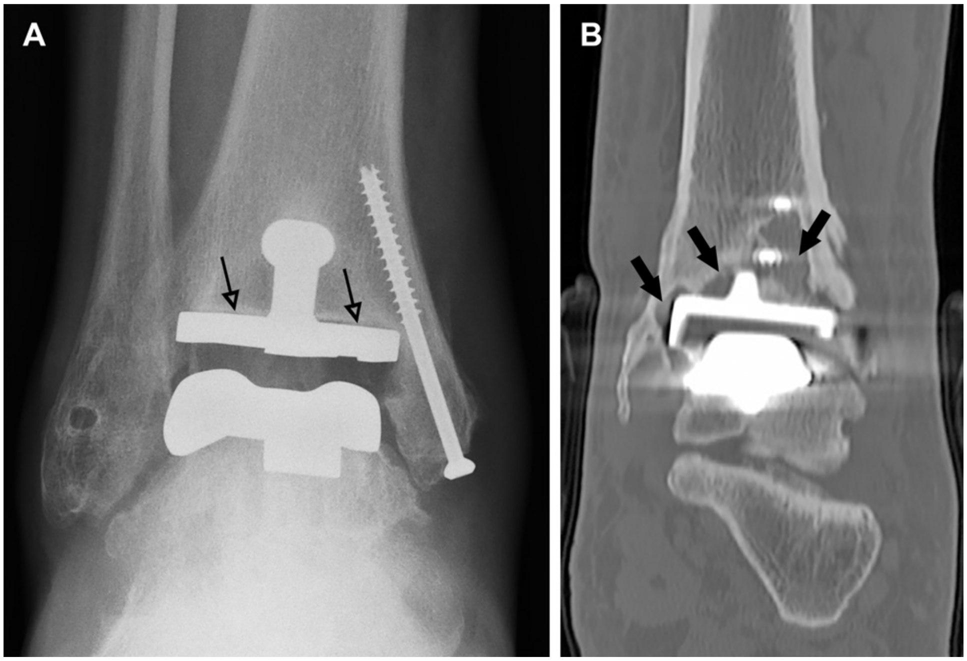


Figure 16. Postoperative TAR findings in two men. **(A)** AP weight-bearing radiograph of a Salto Talaris implant in a 55-year-old man shows an expected area of postoperative radiolucency less than 2 mm in width at the interface with the tibial component (arrows). This is expected to resolve with osteointegration, when the implant gradually fuses with the bone, or to remain unchanged at follow-up imaging. **(B)** Coronal CT image of an Agility implant in a 56-year-old man shows areas of periprosthetic lucency (arrows) wider than 2 mm at the tibial component bone interface. Aseptic loosening is the loss of implant fixation with a multifactorial cause. It may be visualized radiographically as an area of periprosthetic lucency greater than or equal to 2 mm in width.

Imaging-depicted Complications

In addition to the device-specific complications highlighted earlier, there are overarching complications common across all TARs. Glazebrook et al (54) suggested classifying complications on the basis of occurrence rate. High-grade complications (≥50% failure rate) include implant failure, aseptic loosening, periprosthetic osteolysis, and deep infection. Intermediate-grade complications (<50% failure rate) include technical error, subsidence, periprosthetic fracture, and medial gutter impingement. Low-grade complications are rare and include intraoperative fracture and wound healing issues (54). A recent meta-analysis of the most reported complications after TAR showed a deep infection rate of 2%, aseptic loosening rate of 5%, instability rate of 2%, fracture rate of 3%, subsidence rate of 4%, deformity or malalignment rate of 4%, and impingement rate of 6% (55).

Aseptic Loosening

An area of radiolucency measuring less than 2 mm in width that does not progress is a normal finding that represents osseous integration with the bone (Fig 16). Aseptic loosening appears radiographically as an area of radiolucency greater than or equal to 2 mm in width and may progress over time (Fig S1). It may develop from failure of bone in-growth of the prosthesis or an inadequate cementing technique (12). Aseptic loosening has been reported as an indication for TAR revision in up to 40% of patients (56).

Osteolysis

Expansile osteolysis, also known as ballooning osteolysis or periprosthetic cysts, has been reported in up to 15% of TARs and may lead to device instability, periprosthetic fractures, and talar component subsidence (57). Osteolysis traditionally results from an aseptic foreign body reaction to the polyethylene debris induced by macrophage phagocytosis, which stimulates osteoclast activation (Fig 17). However, biomechanical studies of TAR, as compared with total knee and hip replacements, and postsurgical pathologic analysis have shown that factors other than polyethylene wear play a role in TAR osteolysis (58). Other etiologic theories include the presence of elevated synovial fluid, hydrostatic pressure in the ankle joint, inadequate sealing of the bone-implant interface, and chronic repetitive micromotion (59). On images, areas of osteolysis appear as periprosthetic radiolucent areas, which may be cystlike in appearance (Fig 17). These areas may have a thin rim of peripheral sclerosis secondary to an indolent rate of growth.

Subsidence

Subsidence is defined as a change in the vertical position of the talar or tibial component by at least 5 mm (Fig 18) (60). Subsidence of the talar component is more common due to inadequate component stabilization (61). Owing to cementless fixation, rates of subsidence have decreased (24).

Infection

Deep infection rates range from 0% to 5% (62). Prosthetic joint infection may require débridement, antibiotic spacer placement, revision, or conversion to arthrodesis (63). Diagnostic criteria should include a combination of clinical symptoms and serologic markers, such as erythrocyte sedimentation rate and C-reactive protein level. C-reactive protein has a sensitivity and specificity of 90% and 85%, respectively (64). Radiologic findings of deep infection may include periostitis, radiolucency, osteolysis, soft-tissue swelling, and joint effusion (Fig S2) (24).

Medial Gutter Impingement

Clinically, gutter impingement can result in pain and dysfunction. In early studies (65), nearly two-thirds of patients developed impingement. Radiographs demonstrate progressive bone overgrowth in the gutter and joint space narrowing (Fig 6).

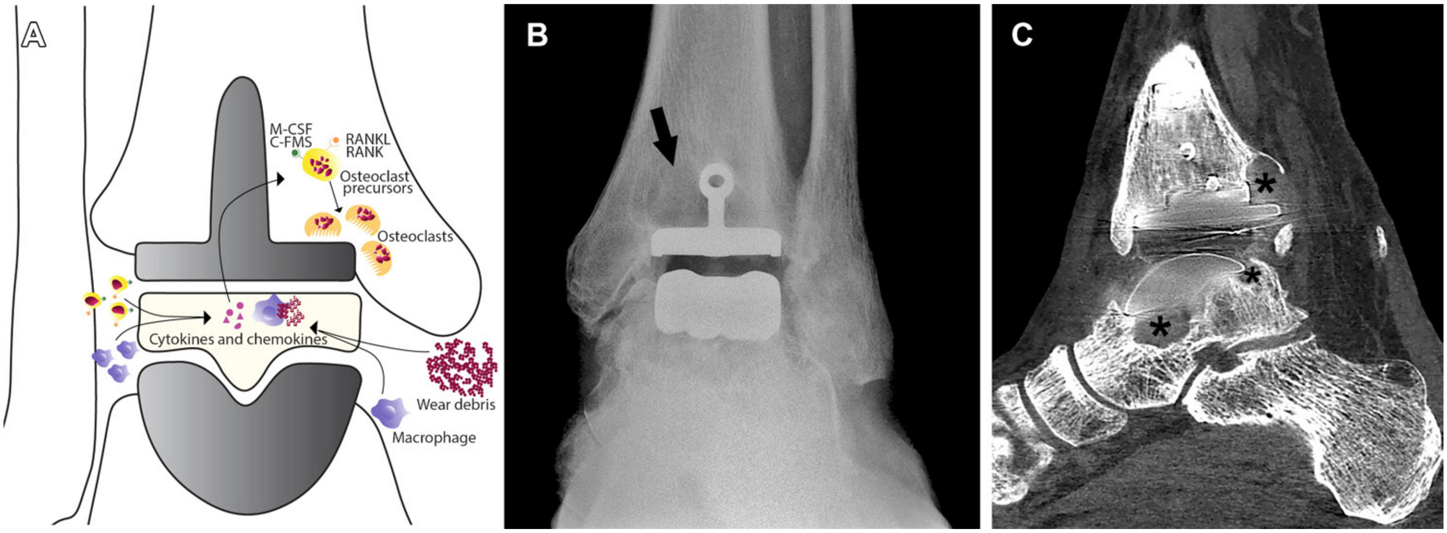


Figure 17. Periprosthetic radiolucency, representing biologic or mechanical osteolysis, in two patients. **(A)** Drawing illustrates the pathophysiology of osteolysis, in which wear debris induces an inflammatory response that stimulates osteoclast activity. **(B)** AP radiograph shows Salto Talaris TAR in a 58-year-old man with cystic osteolysis (arrow) adjacent to the tibial component. **(C)** Sagittal bone-window CT image of Salto Talaris TAR in a 63-year-old woman shows multiple areas of osteolysis (*) due to polyethylene wear and high-pressure fluid mechanics within the ankle joint. *C-FMS* = a type of colony-stimulating factor receptor, *M-CSF* = macrophage colony-stimulating factor, *RANK* = receptor activator of nuclear factor-κB, *RANKL* = RANK ligand.

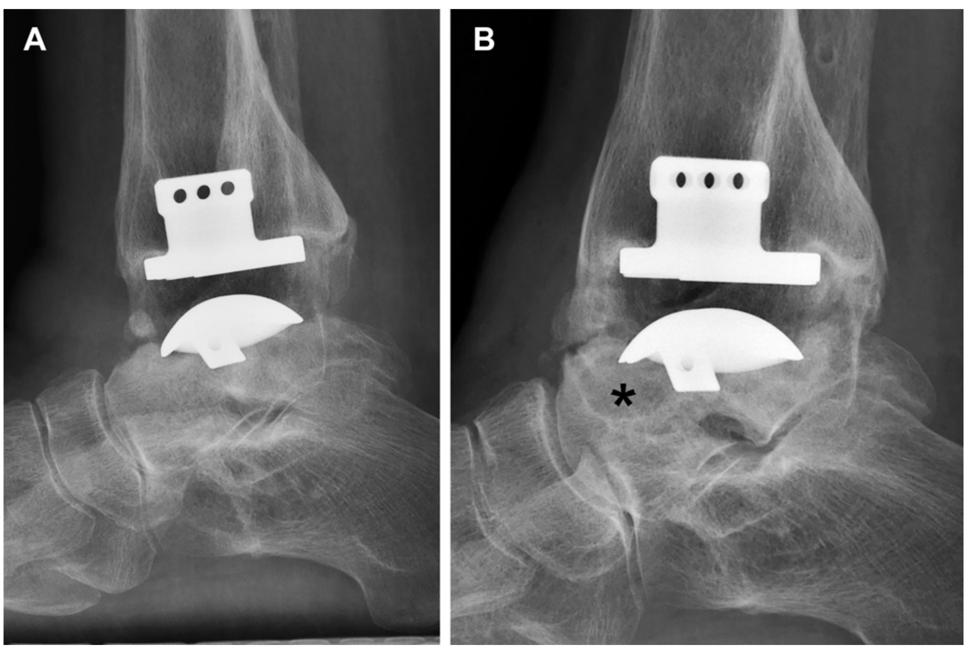


Figure 18. Salto Talaris TAR in a 59-year-old man. Lateral radiographs immediately **(A)** and 3 years **(B)** after implantation show osteolysis (* in **B**) and subsidence of the talar component.

Periprosthetic Fracture

Periprosthetic fractures may result intraoperatively or postoperatively from stress or trauma. Stress-related postoperative fractures may result from overresection of bone, oversized components, or component malposition and impingement. They are most common in the medial malleolus (Fig 12), and most of them are treated nonsurgically (66,67).

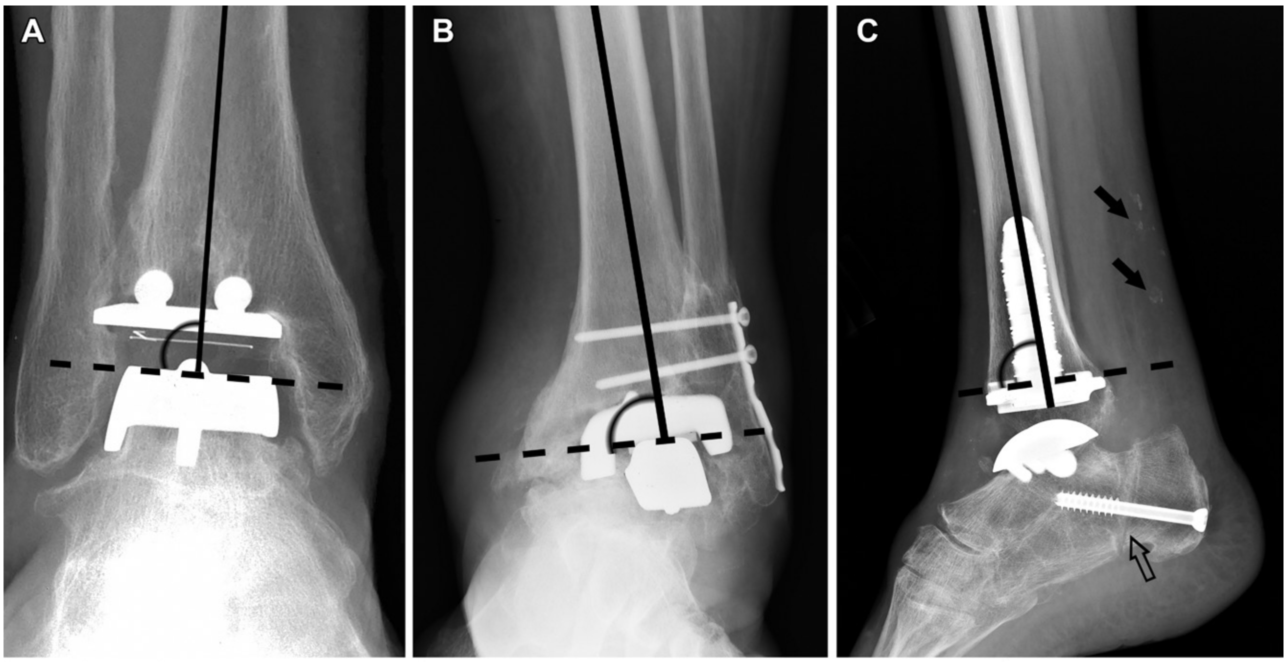
Malalignment

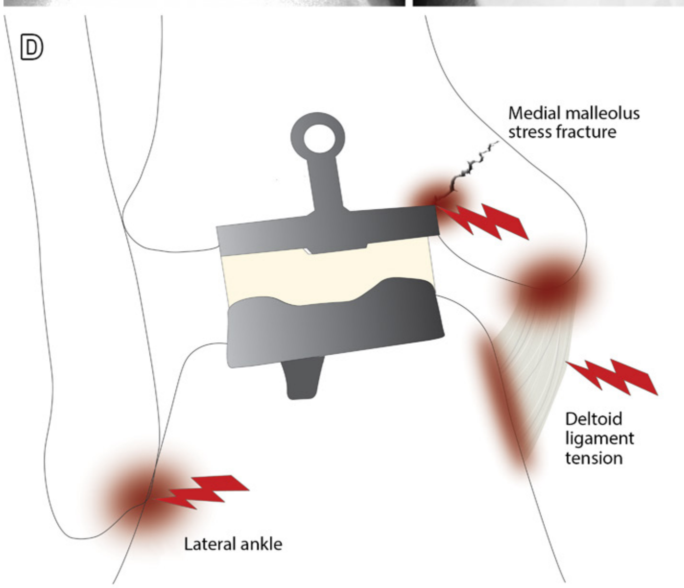
On postoperative images, the tibiotalar angle should be less than 10°. The tibiotalar angle is measured between the long axis of the tibia and a line perpendicular to the talar dome (Fig 19). Negative angles indicate varus alignment, while positive angles indicate valgus alignment. The anterior distal tibial angle on a lateral radiograph should be within 3° of 89° (12). Over time, abnormal varus or valgus alignment can result in altered biomechanics, which can lead to stress fractures, deltoid ligament strain, and/or gutter impingement (Fig 19D).

Heterotopic Ossification

Heterotopic ossification can result in impingement and decreased range of motion after TAR. It has been reported 3 years after surgery in more than 90% of patients (68,69) and is most commonly seen posteriorly (Fig 20). For characterization, a modified grading system based on the hip arthroplasty system is used. Grade 0 represents no heterotopic ossification; grade

Figure 19. Different TAR devices in three patients. **(A, B)** Weight-bearing AP ankle radiographs show TAR with the STAR device in a 66-year-old woman **(A)** and with the Agility device in a 49-year-old man **(B).** The tibiotalar angle, defined as the angle between the long axis of the tibia (solid line) and a line perpendicular to the talar dome (dashed line), is used to assess coronal plane alignment. The angle is normal in **A.** Negative angles indicate varus alignment **(B),** and positive angles indicate valgus alignment (not shown). **(C)** Lateral ankle radiograph of INBONE II TAR in a 65-year-old man shows the anterior distal tibial angle, which is formed by the anatomic axis of the tibia (solid line) and the line connecting the distal points on the anterior and posterior tibial surface (dashed line). Also note the findings of alignment correction surgery, including calcifications in the Achilles tendon (solid arrows) at a prior Achilles lengthening procedure site and correction osteotomy of the calcaneus (open arrow), with concomitant hindfoot triple arthrodesis. **(D)** Misalignment in a valgus or varus position can cause unequal load distribution, predisposing to stress fractures and periprosthetic radiolucency. Drawing illustrates potential long-term complications of valgus malalignment: lateral gutter impingement, medial malleolus stress fractures, and/or pain from deltoid ligament tension.





1, a small island of isolated ossification; grade 2, multiple foci of ossification that are not confluent; and grade 3, confluent bridging ossification (69).

Advanced Imaging

Although AP and lateral weight-bearing radiography is the first-line modality for postoperative imaging of TAR, there may be instances when advanced imaging is useful. Indications for CT include, but are not limited to, a symptomatic prosthesis seen on normal radiographs, suspected infection, characterization of osteolysis, bone stock evaluation, periprosthetic fracture detection, and measurement of varus or valgus alignment with the weight-bearing technique (24,25,70). CT may be limited by hardware-related artifact. Potential methods to reduce artifact and improve visualization include decreasing the number of image sections, increasing kilovolt peak and milliampere-second settings, and using a softer reconstruction kernel. Dual-energy CT methods and iterative metal artifact reduction, when available, also have been performed with excellent results (71,72).

MRI has been described as useful for evaluation of soft-tissue fluid collections (Fig S3), synovitis, and ligaments and tendons (12). US is an alternate imaging method that can be used to assess periprosthetic fluid collections and soft-tissue integrity (Fig S4). It also provides the benefit of image-guided aspiration when a fluid collection is identified.

Nuclear medicine examinations are helpful for workup of aseptic loosening and infection (Fig 21). Technetium 99m (^{99m}Tc)–methylene diphosphonate or hydroxydiphosphonate scanning with blood pool images can depict areas of increased radiotracer uptake that are indicative of abnormal bone turnover (12). Fused SPECT/CT images enable greater accuracy

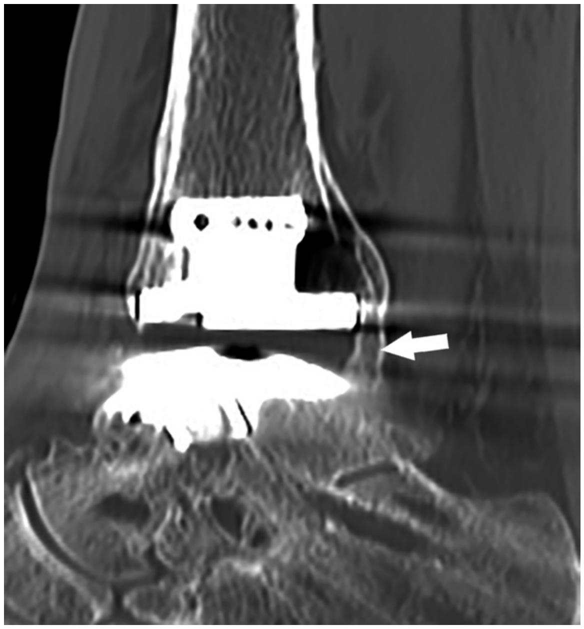


Figure 20. Salto Talaris TAR in a 71-year-old man with impingement symptoms. Sagittal CT image shows grade 3 bridging ossification at the posterior aspect of the tibiotalar joint (arrow).

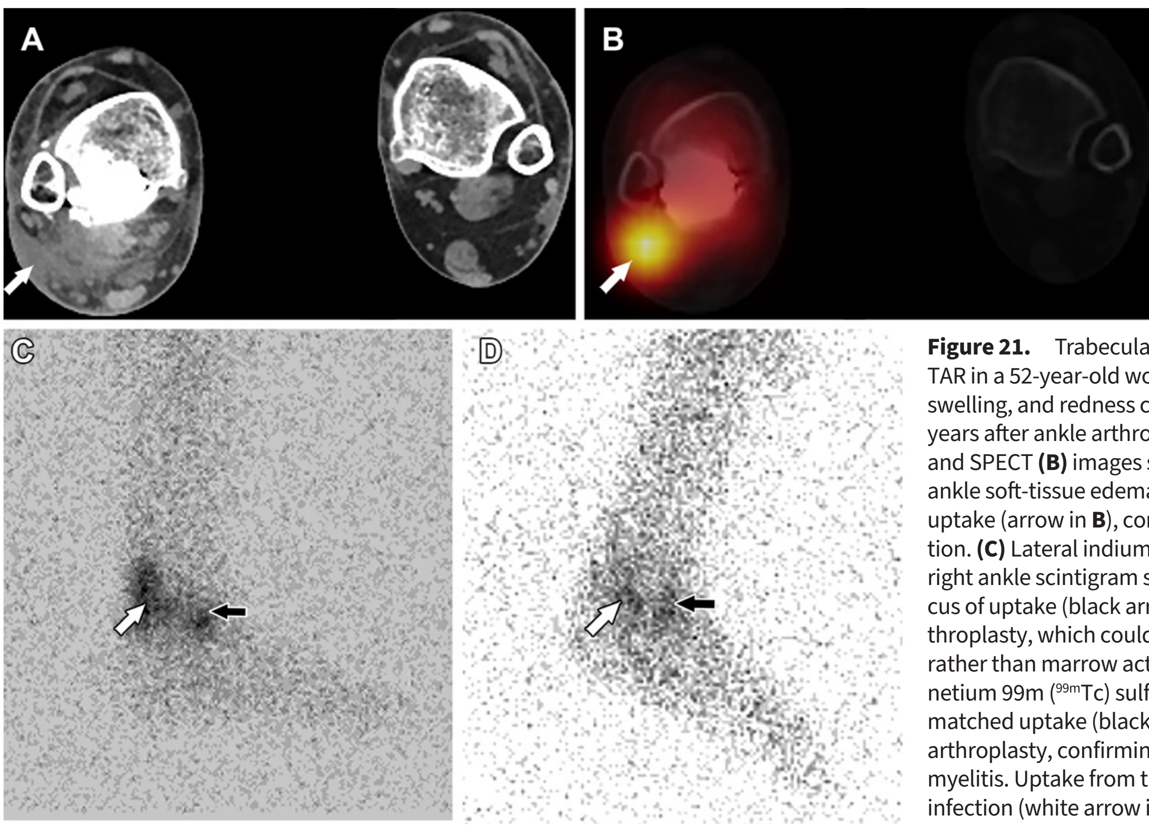


Figure 21. Trabecular Metal Total Ankle System TAR in a 52-year-old woman with right ankle pain, swelling, and redness concerning for infection 2 years after ankle arthroplasty. **(A, B)** Axial CT **(A)** and SPECT **(B)** images show right posterolateral ankle soft-tissue edema (arrow in **A**) and radiotracer uptake (arrow in **B**), consistent with soft-tissue infection. **(C)** Lateral indium 111 (^{111}In) white blood cell right ankle scintigram shows a small nonspecific focus of uptake (black arrow) in the region of ankle arthroplasty, which could represent hardware infection rather than marrow activation. **(D)** Follow-up technetium 99m (^{99m}Tc) sulfur colloid scintigram shows matched uptake (black arrow) in the region of ankle arthroplasty, confirming reactive marrow over osteomyelitis. Uptake from the posterolateral soft-tissue infection (white arrow in **C** and **D**) also is seen.

and localization of the sites of abnormal uptake (73). However, these areas of increased radiotracer uptake at bone scintigraphy are nonspecific. For evaluation of infection, accuracy rates of 88%–98% can be achieved by using a combination of indium-111 (^{111}In)–labeled leukocyte imaging and ^{99m}Tc–sulfur colloid imaging of the bone marrow (74,75). Infection appears as a mismatch between increased radiotracer uptake on the labeled leukocyte study and a corresponding photopenic area on the sulfur colloid study.

Conclusion

TAR has evolved in component design, material composition, biomechanics, and preoperative planning during the past several decades. In this article, commonly used TAR designs, normal radiographic appearances, and imaging complications are reviewed. As the results of longer-term outcome studies on fourth-generation TAR implants are presented, additional complications may be identified. It is important for radiologists to understand the unique features of each design and be able to recognize complications and assess the utility of advanced imaging methods to provide meaningful reports.

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