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Challenges in Total Ankle Arthroplasty

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ABSTRACT

In the past, total ankle arthroplasty was largely abandoned due to poor survivorship most often caused by loss of bone support. High complication rates were also reported. Despite this, there is renewed interest in ankle arthroplasty and encouraging results are seen in survivorship with midterm follow-up. The procedure, however, remains more challenging than total hip or total knee arthroplasty. With the limited soft tissue envelope, wound problems are not uncommon. Forces at the ankle are very large and yet the surface area for prosthetic support is small. Therefore, fixation can be more difficult. The strongest bone can be eccentric at the distal tibia. The tibial prosthesis can, therefore, tend to settle into the softer bone often laterally. Polyethylene needs to be sufficiently thick to maintain its integrity but that requires a larger bone resection, which weakens bone support. Polyethylene failure or wear leads to the majority of failures in hip and knee arthroplasty. There is a need for further basic science research in total ankle arthroplasty. The lessons learned from other arthroplasty should be considered in ankle arthroplasty design.

Key Words: Agility; Angiosomes; Ankle Arthroplasty; Biomimetic Coatings; Bone Support; Buechel-Pappas; Polyethylene; STAR Ankle Arthroplasty

HISTORY

The earliest reports of total ankle arthroplasty were favorable. Stauffer[70] at the Mayo Clinic reported on 63 total ankles with an average follow-up of 6 months. Of these 63 ankles, 52 were rated excellent, six fair, and five poor. In a smaller series with longer follow-up, Lachiewicz et al.[46] reported on 15 total ankle arthroplasties at 39 months postoperatively. All results were excellent or good. Other early series similarly reported encouraging results.[38, 59, 79]

With longer follow-up, however, the reports became more cautious.[21, 29, 30, 66, 76] The terminology used to report results changed. The word ‘‘excellent’’ became rarely used, and instead series often substituted the words ‘‘success’’ or ‘‘satisfactory.’’[76] At times, this only meant that the prostheses were still in place.

In time, virtually all series reported larger numbers of failures.[35, 39–41,52,60,85] Ultimately, almost all authors abandoned or largely abandoned total ankle arthroplasty due to the high failure rate.[29,35,38,40,41,52,60,85] Bolton-Maggs and associates,[11] reporting on 62 total ankle arthroplasties with the ICLH prosthesis, recommended against total ankle arthroplasty. They noted, ‘‘in view of the high complication rate and generally poor long-term clinical results, we recommend arthrodesis as the treatment of choice for the painful stiff arthritic ankle, regardless of the underlying pathologic process.’’ Years earlier, this same practice had reported that their study ‘‘encouraged optimism’’ regarding total ankle arthroplasty.[38] Newton, another early proponent of total ankle arthroplasty, subsequently also reported fusion as the procedure of choice.[60]

Design variations seemed to make little difference. Several authors recommended against constrained designs because of a high failure rate.[39,40,85] However, nonconstrained designs failed as well.[41,60]

Authors who previously performed arthroplasty recommended arthrodesis, which was felt to give more predictable results with fewer complications.[11,35,41,52,60] Schaap and associates[67] reported favorable long-term results with an average of 10 years in patients treated with arthrodesis. There are additional studies which also show favorable long-term results with arthrodesis.[54, 55]

Some authors reported superior gait patterns in the arthrodesis patients, whereas more abnormal

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kinematics and marked muscle weakness were documented following total ankle arthroplasty.[22] Mazur and associates[55] found all patients had favorable gait studies after ankle arthrodesis.

Lord,[51] a French surgeon who performed the first total ankle in 1970, reported disturbances in balance occurring in total ankle arthroplasty patients. These balance abnormalities did not exist in total hip arthroplasty patients and were much milder in total knee arthroplasty patients.[51] There was also noted decreased anteroposterior stability following laboratory total ankle arthroplasties using a meniscal bearing with a flat upper surface.[16] Many years later using the Scandinavian Total Ankle Replacement (STAR) prosthesis, which employs such a design, Garde and Kofoed[26] reported satisfactory stabilometry studies following total ankle arthroplasty.

Summarizing the early experience, it should be noted that initially total ankle arthroplasty was successful. However, these procedures were ultimately abandoned because of the high failure rates. Today's surgeons should therefore still use caution in the optimism with the present designs, which also appear favorable in the early and midterm reports.

COMPLICATIONS AND WOUND HEALING

Total ankle arthroplasty is associated with a high complication rate.[11,21,22,29,30,35,71] The procedure is technically challenging. There is a risk of fracture of one or both malleoli. Neurovascular structures are in close proximity. Laceration of the posteromedial tendons from saw cuts using the anterior approach can occur. Wound healing problems are not unusual.[29,65]

The vascular supply may be more likely compromised by arterial disease at the level of the ankle. As a result of more constricted tethering, the vascular supply of the ankle does not tolerate the dislocation[28] that is done for total hip arthroplasty nor the marked subluxation that is performed at the time of total knee arthroplasty. The soft tissue envelope is sparse at the ankle and has minimal flexibility.[3] At the subcutaneous surface of the tibia where deep fascia is continuous with the periosteum, branches of the anterior tibial artery which supply the skin are easily torn by shear forces.[74] The dorsalis pedis is absent or extremely attenuated in 12% of cases,[3] and this is the main arterial supply to the dorsum of the foot.

ANGIOSOMES

An angiosome is a block or three-dimensional area of tissue supplied by a specific source artery. The angiosome may include bone, muscle, fascia, subcutaneous tissue, and skin. In many areas of the body, such as the forearm, there are rich intramuscular anastomoses between different angiosomes.[74] Four of the five angiosome areas of the leg have blood supply from more than one angiosome. The angiosome supplied by the anterior tibial artery, however, has circulation supported by only one source artery, the anterior tibial artery.[74] For this reason the anterior compartment leg muscles are particularly vulnerable to ischemia. After a vascular insult to the source artery of an angiosome, it is possible for closed or reduced caliber connections termed ''chokers'' to open and supply the structures of an adjacent angiosome. However, this process can take 3–10 days, which places the structures in an angiosome at risk for necrosis when there is only one supply.[3, 4]

The safest incision in the foot and ankle is at the junction of two angiosomes.[4] In this way both sides of the incision are likely to have healthy and independent blood supply. A lateral approach has this advantage. The anterior approach to the ankle, however, divides a single angiosome approximately in the middle. The anterior incision is the one most commonly used for total ankle arthroplasty. This incision is in the angiosome supplied by the anterior tibial artery and its continuation as the dorsalis pedis. The proximal part of the incision may lie in the anterior compartment of the leg where there is greater risk of ischemia. More distally at the level of the ankle and foot there are anastamoses to other vessels, but at this more distal level there are other risks previously outlined.

Either an anterolateral or an anteromedial incision can potentially be at risk. For example, if the neurovascular bundle is retracted laterally, then the two medial anastomoses from the anterior tibial to the posterior tibial vessel are likely ligated or injured. In this situation if the lateral peroneal anastomoses are vestigial or blocked, then healing is at considerable risk. On the other hand, if the surgeon approaches anterolaterally and retracts the vascular bundle medially, then the lateral anastomoses are likely interrupted. In this situation if the medial anastomoses from the posterior tibial artery are ineffective, then again the anterior incision is at considerable risk.

Summarizing, the anterior angiosome itself has only a single arterial source in the leg. The midline anterior approach is less desirable than the border areas between angiosomes. The anastomoses that do exist are at risk and easily injured. Vessel anomaly is common. A suggested plan for the surgeon is to use a doppler preoperatively to map out individual precise circulations.

SUPPORT

The most frequent complication of total ankle arthroplasty in the past has been loss of bone support.

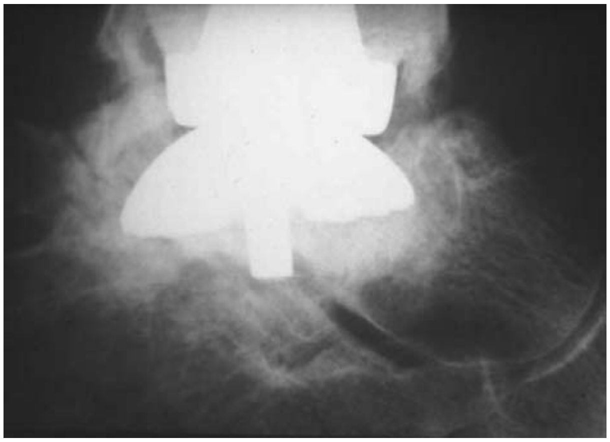

Fig. 1: Talar component subsidence.

Most orthopaedic prostheses depend primarily on bone for support. Unfortunately, however, many patients needing prosthetic arthroplasties have weakened or compromised bone. Past experience with total ankle arthroplasty has shown that loss of support is a primary reason for failure (Fig. 1).

Bone Strength

The importance of bone support was recognized early in total ankle arthroplasty and attention has focused on the increased risks in patients with bone depleted by osteonecrosis, long-term disease, chronic inactivity, or steroid use.[59] An early laboratory study[38] looked at total ankle arthroplasty support by performing total ankle arthroplasties in cadavers and subjecting these arthroplasties to physiologic forces. The study found failure of the support bone around the prostheses in just a few days. Studies of three-dimensional models of talar and tibial components of implanted ankle prostheses have shown that by removing the cortical shell of the talus, abnormally increased stresses are placed on the remaining talar bone.[17] Bone strength at the ankle has been studied and there is marked reduction in the bone strength as the sections are taken farther from the articular surface. The talar bone was found to be 40% stronger than the distal tibial bone, which was noted to be dangerously close to or below the failure point for prosthetic replacement at the ankle (Fig. 2). Distal tibial bone strength should equal or exceed 20 MPa.[33]

The strongest bone is not central nor evenly distributed across the distal tibia, but is in fact eccentric, usually posteromedial[33] (Fig. 3). Since maximum bone strength is eccentric, and strongest in a specific small area reflecting the transmission of the force of heel strike, this can produce a type of pivot point which could lead to tibial component subsidence into the weaker surrounding bone, which is usually anterolateral (Fig. 4).

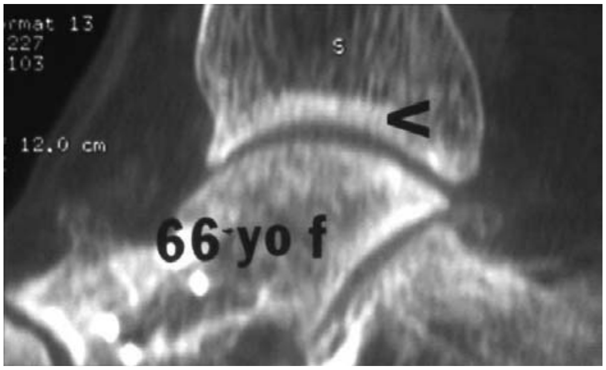

Fig. 2: Minimal amount of strong bone at distal tibia. Arthroplasty resection removes best support bone.

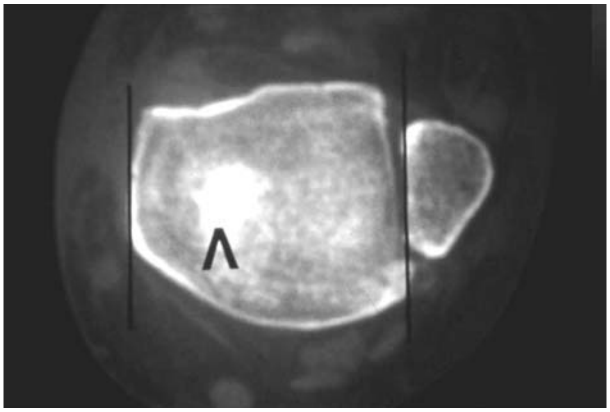

Fig. 3: Area of maximal bone strength is often eccentric.

Force

Forces at the lower extremity are large due to the principle of leverage, which magnifies the force of body weight. Lower extremity forces are particularly increased at the ankle.[2,69–72] Since the forefoot metatarsal pad is a greater distance from the fulcrum at the ankle joint compared to the shorter distance from the ankle to hindfoot, this creates a longer anterior lever arm at the foot. During ambulation, therefore, the Achilles tendon must generate very large tensile forces to overcome the body weight on the longer lever arm of the forefoot. This results in very high compressive forces at the ankle.

Ankle compressive forces are estimated to be three to five times body weight during normal walking.[22,69,72] In one study,[22] marked muscle weakness was documented in ankle arthroplasty patients. Due to their muscle weakness, the total ankle arthroplasty patients did not or were not able to generate a normal compressive load at the ankle. This may be good for prosthesis survival, but not advantageous for ambulation. It should

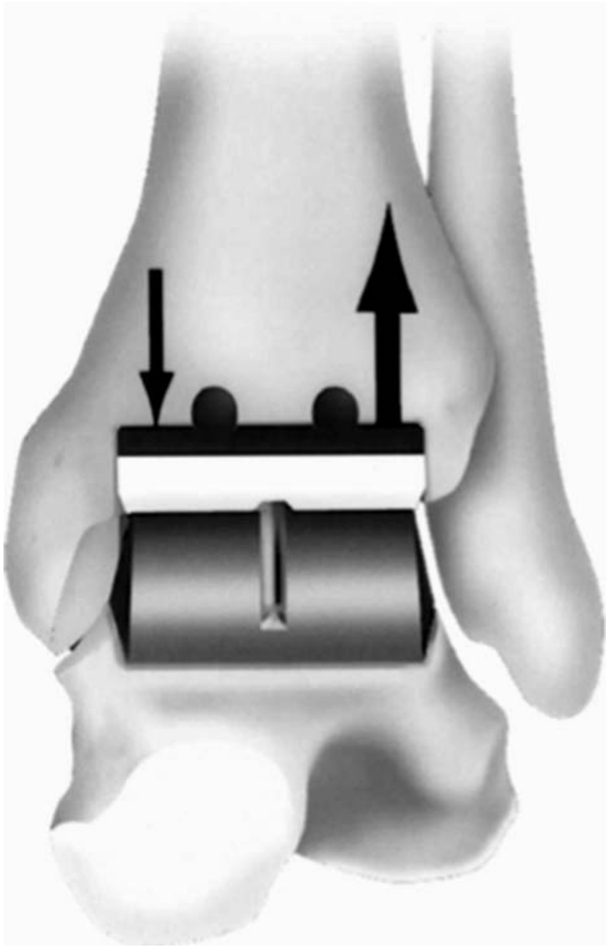

Fig. 4: Eccentric bone support potentially causes uneven prosthetic subsidence.

be noted that the forces at the ankle are large, yet laboratory studies have shown that bone strength is often compromised at this same location.

Surface Area

As the force across the ankle joint cannot be markedly influenced by a prosthetic design, the surface area of contact between the prosthetic component and resected bone becomes critical for success. Forces are commonly measured in Newtons. One Newton equals the force required to lift 1 kg of mass against gravity (1 kg-m/s^2). What is critical in prosthetic design is the *pressure* applied by the prosthesis to the bone. Pressure is a measure of the force per unit area. A Pascal (Pa) is equal to 1 N spread over 1 m^2 (N/m^2). The strength of bone is measured in the same units as pressure (Pascals). Thus, as the surface area is increased, the pressure is decreased, and vice versa.

Early total knees were available in only one size. Often the tibial component was prone to subsidence (Fig. 5A). Today's tibial components are available in multiple sizes allowing better prosthetic support through the expansion of support surface area (Fig. 5B).

The actual surface area of the ankle joint is 12 cm,[2] which is large compared to the hip or knee.[70] Much of this surface area is in the medial and lateral gutters and on the relatively large anteroposterior dome of the talus. Depending on the particular design, much of this surface area may not be available for prosthetic support. The talus is a small bone. When the dome of the talus is resected, this results in approximately one half the surface area as that of the upper tibia at the knee. The compressive force at the knee is three to four times body weight on a larger surface area, whereas at the ankle during ambulation there are compressive forces

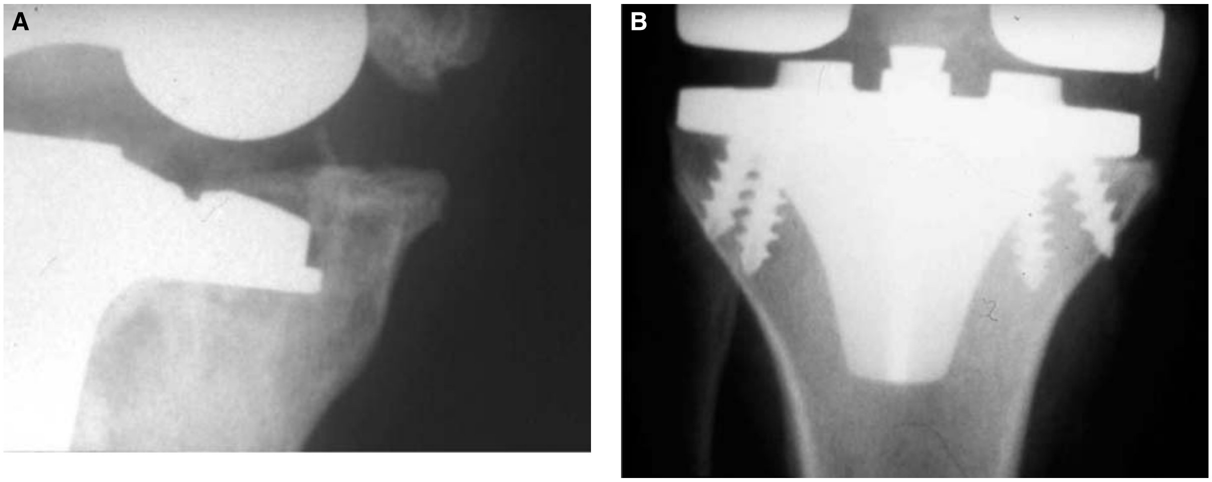

Fig. 5: **A**, Subsidence of a single-sized tibial total knee component with inadequate base plate coverage. **B**, Newer base plates improve bone coverage for better support.

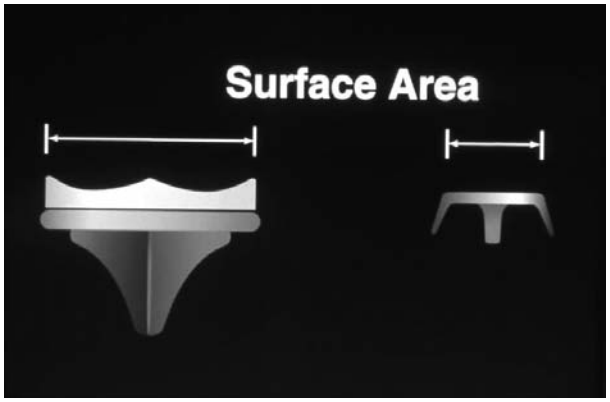

Fig. 6: Smaller surface area for support at ankle.

of up to 5.5 times body weight on a much smaller surface area. This greatly increases the load per unit area (Fig. 6).

The addition of a keel expands surface area, reduces force per unit area, and greatly reduces micromotion.[24, 78] The small size of the talus allows little room for a keel if one is to preserve sufficient support bone. The proximity of the subtalar joint completely prevents the expansion of the keel distally and the confines of the narrow talus prevent expansion of the keel medially and laterally.

The force borne across the ankle is often not central nor equally placed across the prosthetic support surfaces (Fig. 7). Instead the force is often off-center (i.e., eccentric). The eccentric force across the prosthesis leads to a compressive or intrusive force on one side and an elevation or lift-off force on the opposite side.[36, 77] (Figs. 4 and 7). Shear forces also result which increase the stress in the underlying cancellous bone.[7]

Studies in cadaver tibial knee arthroplasties showed that four peripheral screws with a central peg best resists the micromotion of the tibial base plates which results from eccentric force.[77] Another study which included a keel in the selection of base plate designs found that a keel consistently best resists eccentric and shear forces. The worst design of the five designs tested was the tibial base plate with no understructure.[24] At the ankle because of the anatomic limitations of the talus, it may be impossible to provide either four screws plus a central stem or a keel.

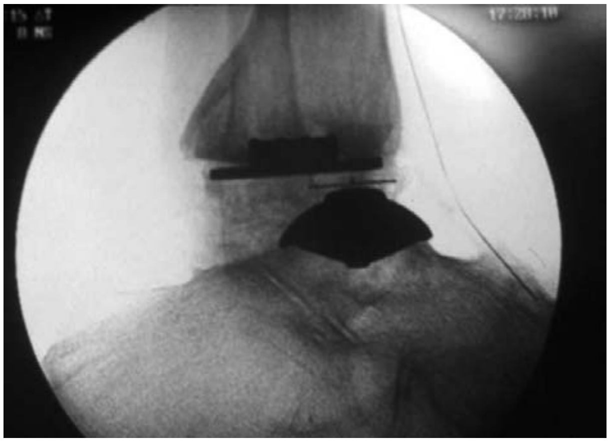

Fig. 7: Stresses across prosthetic ankle may be eccentric.

In summary, it has already been stated that bone strength at the ankle is not evenly distributed but maximal strength is instead eccentric (Fig. 3). Forces that result from normal human activity are also often eccentric. Any malalignment (Fig. 8) may aggravate the eccentric distribution of force in the bone, which is not evenly strong. The eccentricities may not match. At the ankle there is minimal surface area available for the distribution of force and it has already been documented that bone strength is often marginal if not even inadequate. A total ankle arthroplasty is

Fig. 8: Malalignment potentially aggravates eccentric force and resultant subsidence.

therefore always at risk for failure because of inadequate bone support.

MATERIALS: POLYETHYLENE

Initially polyethylene was thought to be a nearly ideal material for arthroplasty. It provides low friction when articulating with metal in vivo. Earlier studies suggested the amount of wear was acceptable and the wear particles were thought to be innocuous.[38] Wear studies suggested minimal wear allowing longevity of 20 years or longer with the available designs.

Clinical observation has proved many of the above assumptions as false and the early laboratory studies as misleading.[10,61,68] There are numerous different patterns of wear and the causes of failure are multifactorial[49,50,68] (Fig. 9). The magnitude of the polyethylene problem is seen clearly in a US report of medical device failures.[20] It is estimated that only 1–5% of such failures are actually reported. A study of 1,717 total hip and 2,769 total knee arthroplasty failures that were reported documents the significance of the polyethylene problem. Polyethylene failure was the most common cause of total hip failures and accounted for 68% of total knee failures.[20]

Early laboratory wear studies often utilized pin-on-disk or linear track motion, both of which provided misleading and overly optimistic predictions.[49, 50] Polyethylene wear is reduced with these types of motion in the laboratory. Clinically, however, the crossing-path type of motion, which occurs in vivo, produces greater wear. Retrieval studies document the severity of the wear (Fig. 9).

We now know that particulate polyethylene debris may cause osteolysis[32, 37] (Fig. 10). Polyethylene particles in sufficient numbers incite a chronic inflammatory process which leads to osteolysis.[37] Particles of small size (less than 15 μm) are phagocytized by macrophages. In response to the phagocytosis of these small sized particles, a cascade of events occurs and the end result is osteolysis. As this progresses, the osteolysis leads to aseptic loosening and eventual loss of support.[32]

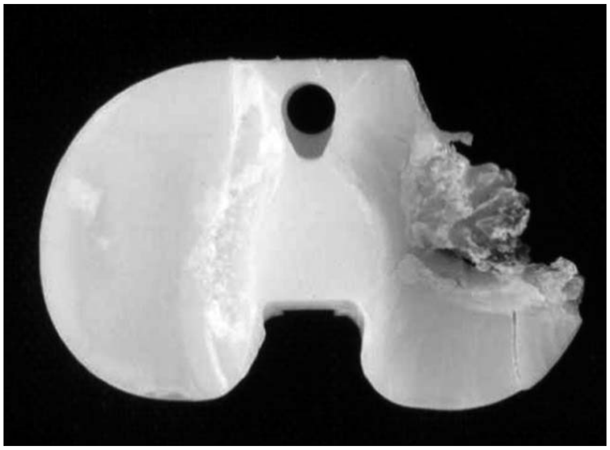

Fig. 9: Complete wear-through of a tibial polyethylene component.

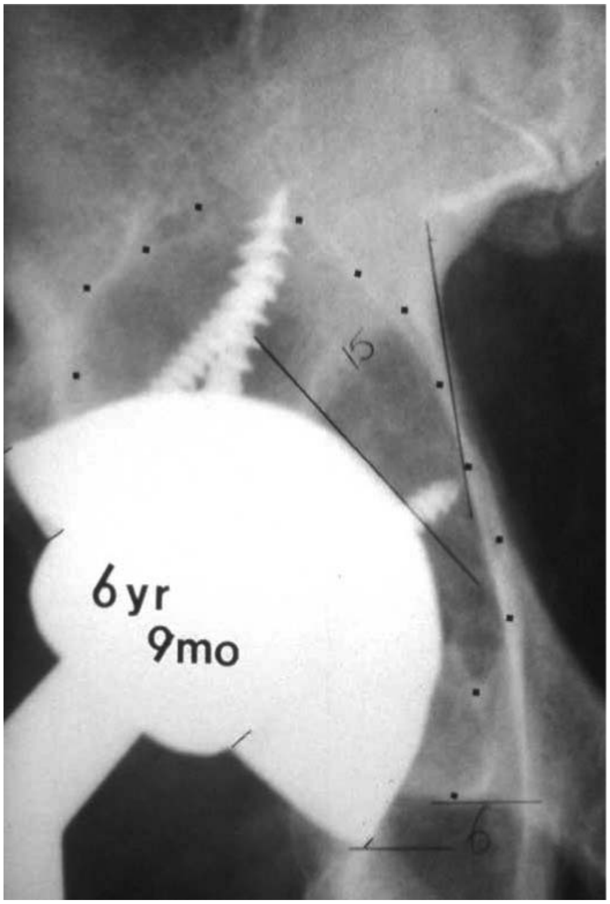

Fig. 10: Large area of osteolysis caused by polyethylene wear in less than 7 years.

The yield strength of polyethylene is relatively low, between 13 and 25 MPa.[10, 84] The developers of the Buechel-Pappas (BP) ankle (Endotech, Inc., S. Orange, NJ) present data showing computed surface contact stresses for the BP ankle on polyethylene to be less than 5 MPa, which is well below the yield strength of polyethylene.[15] This same report notes contact stresses on polyethylene to be 32 MPa for a fixed polyethylene two-component design.[15] The lessons learned during the time of round-on-flat polyethylene total knee designs have shown extremely high failure rates in the past in part due to excessively high contact stresses on the polyethylene. These observations in knee design should be considered in total ankle arthroplasty design.

Thin polyethylene wears faster than thick polyethylene.[6, 7] It is estimated that a minimum of 4–6 mm of polyethylene thickness is needed at the hip and 6–8 mm at the knee where there are larger forces and less conformity. Optimal thickness at the ankle has not been determined.

Metal backing of polyethylene improves force distribution to the nearby cancellous bone and allows in-growth but also requires another 2 mm of bone resection, or decreases the thickness of polyethylene. The metal backing, particularly if there is a lack of polishing, causes backside wear of the polyethylene. Backside wear can be severe in both hips and knees. This underscores the importance of the newer and improved locking mechanisms for polyethylene.

Polyethylene osteolysis was not reported in the early series of total ankle arthroplasty. Early total ankle arthroplasties probably did not last long enough for polyethylene failure to become manifest. Also polyethylene osteolysis was not widely recognized until after the development of cementless fixation. Prior to that time osteolysis was usually thought to be secondary to cement (i.e., ‘‘cement disease’’). We now know that cement disease is actually particle disease and that particulate debris from a variety of different materials, including polyethylene, can contribute to bone loss.[32] Present design total ankle arthroplasties now show improved survival rates and therefore polyethylene problems may become more apparent in total ankle arthroplasty.

Fracture of the mobile polyethylene component had been reported in separate series of STAR (Waldemar Link GmbH & Co., Hamburg, Germany) arthroplasties.[19,43,80] The typical history is a sudden catastrophic event followed by pain and swelling in the involved ankle.[43] This has occurred rarely and most commonly in physically active people such as hikers.[43] The phenomenon of edge loading on the polyethylene component of total ankle arthroplasties has been reported.[80,81,83] This causes excessive wear and is described in a recent review of 200 STAR ankle arthroplasties.[83] Polyethylene failures have also been reported due to excessive wear in the BP total ankle.[15]

Osteolysis has been reported with both the Agility (DePuy, Inc., Warsaw, IN) and STAR prostheses.[62,80,83] Although most reports are of radiographic findings, the presumptive etiology is polyethylene osteolysis as is commonly seen in hip and knee arthroplasty.

The failures of polyethylene have led to the search for improved polyethylenes as well as for alternative bearing surfaces. Past attempts to improve polyethylene include the development of Poly II and Hyalmer.[49] Poly II included a composit of carbon fibers which were added to reduce creep (cold flow) of polyethylene. Hyalmer is polyethylene with altered polymer morphology. In clinical usage, however, both ‘‘improvements’’ failed in the sense that their performance was inferior. These products have been discontinued for total joint usage. Although laboratory tests suggest greatly improved wear characteristics with the newer highly cross-linked polyethylenes, the effects of this process on fatigue and fracture resistance properties of the polyethylene are not yet known.[49] It is important to remember that past attempts to improve polyethylene have failed to provide superior performance in vivo.[50]

FIXATION

The early total ankle arthroplasties used polymethylmethacrylate cement for fixation. This fixation was often lost, however, when the bone support failed, which was the most common mode of failure. Virtually all current ankle arthroplasty designs employ cementless fixation which potentially offers a more permanent long-term bond provided the bone support is not lost.

A study of cemented stainless steel metal and polyethylene total ankle arthroplasties compared with uncemented ceramic-on-polyethylene total ankle arthroplasties recommended the cementless technique.[73] Since the cementless ankles were an average of only 4.1 years postoperative, whereas the cemented ones averaged 8.1 years postoperative, meaningful conclusions regarding the use of cement or cementless technique are not clarified in this comparative study.

There is a paucity of laboratory study on cementless fixation in ankle arthroplasty. However, recent clinical series which use cementless fixation report successful midterm survivorship.[1,13,15,43,44,62,80,81–83] Those results are improved compared to earlier series.[11,29,35,38–41,52, 60, 85]

Cementless fixation occurs with on-growth onto the surface of a prosthetic component or in-growth into a roughened coating applied to the surface of a prosthesis. In-growth can occur into a roughened surface such as that obtained with sintered beads, plasma spray metals, or fiber metals. These roughened microsurface treatments are added as an external layer on to the surface of the prosthesis.

Osteoconductive coatings may be added also in order to stimulate bone growth at the bone–prosthesis interface. Calcium phosphate ceramics such as hydroxyapatite can be applied to the prosthetic surface with a plasma spray technique. This technique as a line-of-sight process tends to coat the high spots on the outside of the roughened coating and misses the inner surface of a three-dimensional microstructure coating.

The newer biomimetic coating techniques involve a precipitation in a supersaturated $Ca\ (PO_4)_2$ solution done at low temperatures. As an immersion technique this has the ability to coat more fully the inner geometry of a three-dimensional microstructure surface coating applied to a prosthesis.[27] The potential benefits of bioactive coatings are the improved strength of bone prosthetic bonding, an accelerated response of the bone at the implant junction, improved filling of gaps, and the elimination of the fibrous layer that can occur between the prosthesis or cement and bone.

Both laboratory and clinical investigations support the use of hydroxyapatite[18,75] but the success can vary according to the specific prosthetic component treated,[27,47,57,63] the specific area of use, and whether or not there is a roughened surface treatment.[9] For example, hydroxyapatite added to a smooth femoral hip arthroplasty component has shown long-term success, whereas this same treatment on a smooth acetabular component has shown a much higher failure rate.[9,47,57,63] This is another example, beside that of polyethylene, of a material transfer phenomenon where a material may not behave in the same fashion when transferred to a different area. Therefore, success at the ankle would not be necessarily assumed simply because of the success on the femoral components of total hip arthroplasties.

In the United States, ankle prosthetic components are sold without bioactive coatings. The Agility total ankle arthroplasty has a porous-coated cobalt chrome surface. The BP has a beaded titanium surface for in-growth. The STAR prosthesis in current use in the United States is a titanium porous coating on a cobalt chrome prosthesis without hydroxyapatite or calcium phosphate. This prosthesis is made available to selected surgeons who are part of a multicentered study.

Bioactive coatings have been added to total ankle arthroplasty components in Europe and Japan. The TNK prosthesis (TNK ankle, Nara, Japan) has a ceramic component coated with hydroxyapatite. Two ankle designs similar to the BP sold in Europe, the Alphanorma OSG ankle (Corin Group Co., Quierschied, Germany) and the AES (Ankle Evolution System) (Biomet Merck Valence, Cedex, France) ankle have a double coating surface which includes hydroxyapatite. The HINTEGRA ankle (New Deal Co., Vienne, France) has a double-coated porous titanium and hydroxyapatite surface. In the year 2000, the STAR prosthesis was made available in Europe using a dual coating of calcium phosphate which is electrochemically bonded onto a titanium porous coating which is applied to the cobalt chrome prosthesis. The advantage of the electrochemical application of calcium phosphate is that this process allows better distribution of the bioactive surface throughout the interstices of the microstructure of the titanium coating since it is an immersion process. The above ankles sold in Europe are examples of the ‘‘second line of defense’’ concept in surface treatment.

In a review of 200 cementless STAR total ankle arthroplasties, Wood noted significantly improved radiologic appearance in the newer dual-coated STAR prostheses compared with the earlier hydroxyapatite-coated cobalt chrome prostheses.[81,83] Similarly, Bonnin[12] reported improved radiologic appearance on the bioactive coated Salto Total Ankle prosthesis compared to earlier Salto ankle arthroplasties without the bioactive coating.[12]

DESIGN

In speaking of total knee design, John Insall stated that knee arthroplasty design was based more on opinion than scientific study.[34] The same may be true for ankle arthroplasty. There have been comparatively few laboratory studies on the design criteria for total ankle arthroplasty. Falsig and associates[25] looked at stress transfer to distal tibial trabecular bone with three different generic tibial designs at the ankle as follows: (1) a polyethylene tibial component, (2) a metal-backed polyethylene component, and (3) a long-stem metal-backed tibial component using a much longer stem than is common. With these three designs, an eccentric anterolateral load of 2,100 N (approximately three times body weight) was applied and compressive stresses in the bone were measured. The authors found a 25% reduction in trabecular bone stress to 15 N/mm^2 by adding metal backing to the polyethylene component. Shear stresses were also reduced. The addition of the long stem, however, resulted in almost complete reduction of trabecular bone stress in the distal tibial bone since most stress was transferred to the long stem. The authors postulated that this situation may lead to excessive stress shielding in the distal tibial bone and therefore could adversely affect a long-term clinical result.

Based on the few available laboratory studies looking at bone strength at the ankle[33] and total ankle arthroplasty studies[17,48] as well as the information available from hip and knee arthroplasty, it appears that goals for total ankle arthroplasty may be as outlined in Table 1.

Review of these goals show that some are difficult to achieve or even contradictory. Achieving goal 4 (i.e., use thicker polyethylene), for example, directly inhibits the ability to achieve goal 1, which is to minimize bone removal. Furthermore because of the small size of the distal tibia and talus, goals 2 and 3 (maximizing surface area for support and stabilization) are very difficult to achieve.

Designs vary considerably in the amount of bone area resurfaced in total ankle arthroplasty. Although data are not available providing guidance on how much area at the ankle should be resurfaced, from a force distribution standpoint it is desirable to maximize the area for resurfacing. On the talar side, the STAR maximizes the area of resurfacing by including the

Table 1: Goals for the design of a total ankle arthroplasty

Goal 1:	Minimize bone removal on both sides of the joint.
Goal 2:	Maximize the surface area for support of the prosthesis.
Goal 3:	Maximize the surface area for stabilization of the prosthesis, but without excessive bone loss and without an excessively long stem.
Goal 4:	If polyethylene is used, allow sufficient thickness of polyethylene as well as a conforming geometry.
Goal 5:	Establish the proper balance between constraint and freedom.
Goal 6:	Use a bearing surface that minimizes wear.
Goal 7:	Use a firm, expanded surface-area locking mechanism for ankles that use a fixed, nonmobile polyethylene.
Goal 8:	Improve instrumentation to help ensure proper alignment to minimize shear, angular, and eccentric forces.

medial and lateral talar facets in addition to preserving part of the dome of the talus. Theoretically this may improve force distribution and long-term stability of the talar component.

It has not been determined, however, if it is in fact necessary to resurface the medial and lateral facets. The BP ankle is an on-lay component of the superior surface of the talus only with two fins in the talar dome. By not resurfacing the medial and lateral talar facets, less cortical bone is removed from the talus. Saltzman points out that with each additional area resurfaced greater operative exposure and more bone removal are required.[65]

Without resurfacing the medial and lateral talar facets, there is a theoretical concern of persistent postoperative pain from the nonresurfaced facets. However, surgeons experienced in both the STAR and BP total ankles report that medial and lateral facet pain has not been a clinical problem with the BP ankle.[64,81] Rippstein has found that it is not necessary to resurface the facets.[64] With regard to resurfacing of the facets, the trade-off therefore is the potential benefit of increased surface area for stability and fixation by including facet resurfacing versus the potential benefit of preservation of the strong medial and lateral cortical bone by not resurfacing these areas.

Kinematics

Arthroplasty alters normal kinematics at the ankle. Rather than being a simple hinge joint, Michelson et al.[56] found that the ankle moves ‘‘as a complex joint with coupled three-dimensional motions.’’ The talus is wedge shaped with different radii of curvature on the medial and lateral talar domes as well as different radii of curvature anteriorly and posteriorly.[5] Therefore, the ankle joint axis changes continuously throughout the range of motion.[53] The axis of motion can vary considerably and may vary among different individuals.[5, 53]

With the exception of the HINTEGRA, most current ankle arthroplasty designs do not employ a different radius of curvature on the medial and lateral aspects of the talus. In the normal anatomy, there is a slightly smaller curvature medially. Theoretically, an arthroplasty with symmetric equal curvatures on the medial and lateral aspects of the talar component could result in a ligamentous imbalance which is tight medially and loose laterally. In arthroplasty designs with a mobile bearing, the flat geometry on the upper side does not reproduce the convex-concave articulation of the talus in the tibial mortis. The normal anatomy, therefore, has more inherent anteroposterior stability. Theoretically, the lack of the convex-concave shape in the sagittal plane puts more stress on the ankle ligaments. Proper ligamentous balance and stability therefore may be even more important following prosthetic replacement than in the normal ankle, especially in a relatively unconstrained prostheses such as the STAR, BP, and HINTEGRA. Despite the potential advantage of a more physiologic tensioning of ankle ligaments with a truncated talar component, the BP and STAR arthroplasties appear to work well in the hands of experienced surgeons.[15,45, 83]

Bearing Surfaces: Fixed vs. Mobile Bearings

Present total ankle arthroplasty designs use a polyethylene-bearing surface. The Agility polyethylene measures from 3.73 mm to 4.7 mm and additional plus 2-mm inserts are available.[23] Other popular designs also have relatively thin polyethylene when compared to total knee arthroplasty in which 6–8 mm is recommended. Since bone cuts must be kept conservative, there is not sufficient room remaining to allow two metal components that are a minimum of 2–3 mm in thickness each and still allow sufficiently thick polyethylene. A fixed polyethylene-bearing surface may potentially reduce backside wear if there is an effective locking mechanism. The Agility ankle and the Eska developed in Germany use a fixed bearing.

A mobile bearing by definition allows backside wear but may be made fully conforming, which greatly reduces contact stress in the polyethylene. Most newer design total ankle arthroplasties use a mobile bearing. In the United States, mobile bearings are used for the STAR and the BP ankles. In Europe, in addition to the STAR and BP (Wright Cremascoli Ortho S.A., Toulon-Cedex, France), the HINTEGRA, the AES, the Salto, and the Alpha-norma OSG ankle all use a mobile bearing. An advantage of the mobile bearing concept is that the flat upper surface allows some rotation which reduces stress at the prosthesis–bone interface. A potential disadvantage is that the flat geometry does not reproduce the convex-concave articulation of the talus in the tibial mortis. Studies that look at ankle stability after prosthetic replacement show conflicting results, although some studies document increased instability.[16, 26, 51]

The BP ankle design may allow better contact at the bearing surface because of its curving geometry under adverse loading conditions, such as tilting due to malalignment or ligament imbalance.[81] Even the mobile bearing STAR design may be prone to edge-loading.[81] Fixed two-component designs can be prone the problem of edge-loading especially if there is any malalignment. Edge-loading will increase contact stresses in the polyethylene.

A review of the three ankle arthroplasty designs in current use in the United States follows.

Agility[1] (Fig. 11)

- The Agility ankle employs a unique feature of an arthrodesis of the distal fibula to the distal tibia at the time of surgery. This expands the surface area available for support on the tibial side by utilizing the distal fibula for additional support. A nonunion of this important arthrodesis, however, risks loss of fixation on the upper side.
- The polyethylene insert into the metal-backed tibial component is concave in the sagittal plane. This adds anteroposterior stability.
- A deliberate mismatch exists between the larger upper tibial component and the smaller lower talar component. This mismatch allows the talus to seek its own position and allows freedom from excessive constraint protecting bone–prosthesis interfaces.
- The deliberate mismatch in sizing of components could potentially allow increased contact stresses in the polyethylene if any malalignment or ligament imbalance led to ‘‘edge-loading’’ of the talar component.
- The polyethylene component is relatively thin. It does not have the expanded surface area for fixation of polyethylene as used in the newer locking mechanisms. The locking mechanism relies on a medial and lateral peg only as well as a posterior stop as opposed to a circumferential or multiple fixation point locking mechanism. Without any anterior capture it does not circumferentially capture the polyethylene as in many of the newer locking mechanisms.
- The prosthesis resurfaces the tibiotalar surface as well as the medial and lateral facet areas.
- The talar component requires a relatively aggressive talar cut leaving less talar bone available for support.
- The early talar design did not take advantage of the entire available surface area for support. A modified newer version partially improves this situation.
- Insertion of the entire prosthesis requires relatively aggressive bone cuts. A distracter used at the time of surgery helps reduce this problem but the amount of bone removal is still substantial.

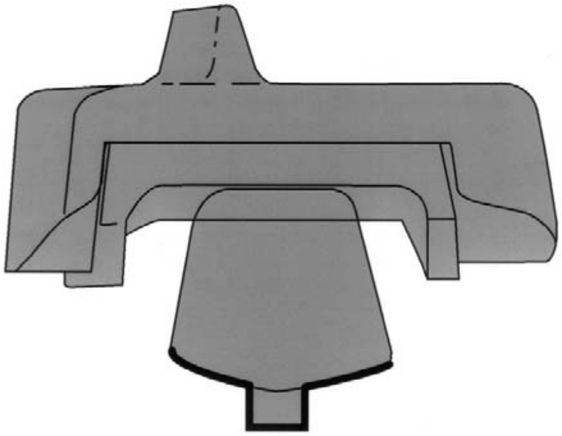

Fig. 11: Agility ankle prosthesis. The upper component includes a polyethylene insert.

Buechel-Pappas Total Ankle[8,9] (Fig. 12)

- BP total ankle is a three-component design, which utilizes a mobile polyethylene bearing.

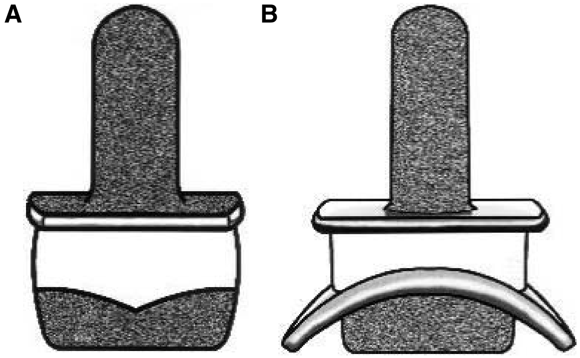

Fig. 12: Anterior A and lateral B, views of Buechel-Pappas total ankle prosthesis.

- The mobile bearing reduces excessive stress transfer to the bone–prosthesis interface.
- There is full conformity between the polyethylene component and the tibial and talar components.
- The prosthesis resurfaces only the tibiotalar area and not the facets.
- Because the bearing is mobile, there is automatically backside wear.
- The tibial component has a short stem. This may potentially protect tibial trabecular bone but avoid the excessive stress shielding from an overly long stem.
- The talar component is an on-lay component with two fins for fixation. It preserves most of the talar dome. Since it does not resurface the medial and lateral talar facets it thereby helps preserve talar cortical bone.
- The flat upper surface of the mobile bearing may reduce anteroposterior stability.

Star[30, 31] (Fig. 13)

- This prosthesis also has a mobile bearing polyethylene component.
- The prosthesis resurfaces the tibiotalar articulation and provides a hemi-resurfacing of the two facet areas.
- There are two dowels for tibial component fixation. This presents a lower surface area for stress distribution in the distal tibia compared to the BP ankle but might also reduce stress shielding from a stem.

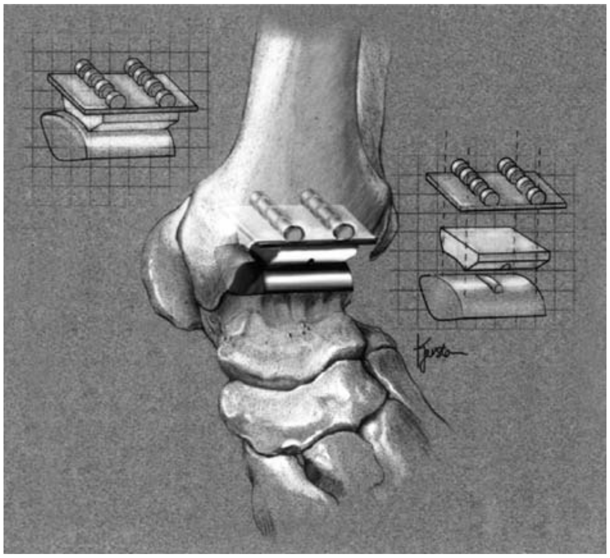

Fig. 13: The Scandinavian Total Ankle Replacement (STAR) prosthesis.

- Talar bone cuts remove less bone than is commonly removed with the Agility ankle.
- Talar fixation is enhanced by medial and lateral resurfacing which expands the surface area for support on the lower side. Therefore, surface area for fixation and load distribution is maximized on the talar component. The removal of medial and lateral facets decreases the amount of remaining cortical bone.
- The flat upper surface of the mobile bearing may reduce anteroposterior stability.[10]

All three ankle arthroplasties have shown acceptable short-term and midterm results in clinical trials.[1,13–15,19, 42,43,45,62,80,81, 83] Longer term follow-up is not yet available.

SUMMARY

The stimulus for total ankle arthroplasty derives from a partial dissatisfaction with ankle arthrodesis[49, 58,59] as well as success seen with total hip arthroplasty and total knee arthroplasty. Total ankle arthroplasty is more challenging than total hip arthroplasty and total knee arthroplasty due to the limitations of bone strength, the marked limitation of the anatomic size of the talus, and the magnified compressive forces distributed across the ankle due to the longer lever arm of the foot. Healing problems are also much more common at the ankle. Early total ankle arthroplasties were initially successful and reported as ''excellent.'' However, with longer follow-up these failed largely due to insufficient bone support.

Bone support at the ankle may be marginal. The strongest bone is often eccentric. Forces may also be eccentric causing a compressive force on one side of a prosthesis and lift-off force on the contralateral side. Malalignment may aggravate eccentric loads on prostheses causing compressive forces on weaker underlying bone. Forces are large at the ankle but the surface area for support is small. There is little to no room to provide a keel in the talus and a keel has been shown to best resist eccentric forces. Polyethylene has been the primary cause of arthroplasty failure in the hip and knee leading to interest in alternative bearing surfaces. Current ankle arthroplasty designs use polyethylene.

Successful design of total ankle arthroplasty has been far more challenging than at the hip or knee. There is a paucity of laboratory studies of ankle arthroplasty to help guide appropriate design. Laboratory investigation is essential and will hopefully improve the long-term success with this procedure and prevent another series of failures.

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