The megaprosthesis is designed to reproduce the form and function of a removed or lost large segment of bone and accompanying soft tissues. Slow but substantial improvements in the design and surgical implementation of these devices have advanced the capacity to restore patients’ functional abilities. The essential challenges include identifying the ideal materials, bonding these materials to bone and soft tissues, reproducing functional anatomy, and adapting to the growing skeleton. Failure of these devices can result from soft-tissue insufficiency, aseptic loosening, structural failures, infection, and tumor recurrence. The history of the use of megaprostheses in the pelvis, proximal femur, distal femur, total femur, and proximal tibia has shown that each anatomic area presents unique challenges. Improvements that have been made over the years will guide the development of the next generation of devices. Despite early high complication rates, these devices are a reasonable choice in the right patient.
The next step in the evolution of these implants consisted of attempts to eliminate aseptic loosening. One way to achieve this goal was to avoid the use of cement and obtain bony integration into the prosthesis. Thus, interface engineering was attempted with porous-coated metals and hydroxyapatite coatings. Advances in the materials used for the articular surfaces were made in primary arthroplasty and incorporated into megaprostheses, including the use of high-molecular-weight polyethylene in an attempt to decrease the generation of wear particles.

Soft-tissue attachment has been a problem since the advent of megaprostheses because the removal of a large segment of bone necessitates removal of the muscular and tendinous bone attachments. Techniques to improve implant adhesion include the use of suture through configurations of holes, braided metal cable, meshes such as Marlex mesh (Chevron Phillips Chemical), Gore-Tex (W. L. Gore & Associates), and aortograft (Gore Medical) with Dacron (Teleflex Medical) tape. The ideal soft-tissue attachment technique depends substantially on the anatomic considerations at each site.

**Anatomic Considerations**

**Pelvis**

Pelvic tumors are some of the most challenging tumors to manage surgically. The challenges involve navigating complex anatomy, minimizing morbidity, and preserving function in an area of substantial stress between the lower extremities and axial skeleton. Complications include a high infection rate, hardware loosening, and intraoperative injury. Options for the management of these defects range from no reconstruction to reconstruction with allografts, allograft-prosthetic composites, saddle prostheses, or noncustom and custom megaprostheses. Early surgeries to remove part of the pelvis were recorded by Jaboulay, by Cacciopoli, and by Girard, who performed a successful external hemipelvectomy in 1895. In 1979, Eilber et al were among the first to describe internal resection. In the late 1970s, reconstruction, including with megaprostheses, began to be more common. In 1978, Johnson described a reconstruction including a standard Charnley hip prosthesis with a large methyl methacrylate spacer secured by Kirschner wires. In 1979, Burri et al used polyacetyl resin in three patients, fixing the prostheses with screws and clamps in a variety of arrangements. Between 1980 and 1997, Wirbel et al used custom polyacetyl resin prostheses or Vitallium prostheses (Howmedica or ESKA) with computer-aided design. Most of the 17 patients who were available for follow-up had good or excellent outcomes, but >50% required crutches for ambulating outdoors. Reported complications included infection, hip dislocations, and anchorage loosening. Additional studies confirmed the high risk of deep infection, hematoma, or dislocation of the prosthesis, up to 42%. Abudu et al described the use of custom prostheses in 35 patients between 1971 and 1994. In 17 patients, they used a two-stage procedure in which the prosthesis was constructed from a mold made from a portion of the pelvis excised in the first stage and was implanted 6 weeks later. In 18 patients, they employed a single-stage procedure with the use of CT scans for preoperative implant design (Figure 1, A).

Other modalities of reconstruction in patients with pelvic lesions have included saddle prostheses (Figure 1, B). These prostheses have been demonstrated to be useful in some patients, but their limitations are their high dislocation and infection rates and the wear that occurs as the prosthesis erodes the iliac bone. An additional reconstruction option is the cone or pedestal prosthesis, which
avoids a large reconstruction and relies on bone ingrowth into the prosthesis from the strong posterior column bone. Bus et al.\textsuperscript{18} reviewed their experience with this type of prosthesis between 2003 and 2009, reporting a 5-year survival rate of 61%.

As mentioned previously, the decision to reconstruct the pelvis after resection has been debated throughout the years. The substantial risks of postoperative infection and hardware complications have led many surgeons to recommend leaving the leg flail or using limited fixation of bone and/or soft tissues with wires, mesh, sutures, or suture tape to obtain some soft-tissue coverage before allowing the limb soft tissues to scar in. A review of pelvic tumor resections at the Mayo Clinic from 1970 and 1989 included 38 patients, none of whom underwent reconstruction: the extremities were either fused or left flail.\textsuperscript{19} Angelini et al.\textsuperscript{20} more recently reviewed their results of pelvic reconstruction and demonstrated infection rates of 15% without reconstruction and 26% with reconstruction.

**Proximal Femur**

The proximal femur megaprosthesis is one of the more frequently used megaprostheses in orthopaedics. An early proximal femur endoprosthetic reconstruction was reported in 1949, when Seddon and Scales\textsuperscript{21} used a hand-carved polyethylene (alkathene) prosthesis to replace the proximal two-thirds of the femur in a 12-year-old boy with polyostotic fibrous dysplasia, thereby preventing the need for hip disarticulation surgery. In 1951, a similar prosthesis made of methyl methacrylate was used in a 45-year-old man. Initial fixation of some of the early devices included slotted metal plates and nuts with bolts. Further modifications, reported in 1981, included the use of monoblock metal implants made of cobalt-chromium proximally and titanium distally for the stem.\textsuperscript{22} The problem of stem fracture was addressed by improving the metal manufacturing techniques and by increasing both the diameter and the length of the stem. Titanium has increasingly become the material of choice for stems because it has a modulus of elasticity similar to that of bone. In 1981, Sim and Chao\textsuperscript{23} published an early series of 32 patients who underwent proximal femoral arthroplasty for reasons other than tumor. The device used in their study was a solid monoblock implant made of Vitallium and manufactured in various sizes. For the acetabular implant, a cemented polyethylene cup was used. Complications included dislocations, delayed deep infections, and fractures.

Fixation to the femur can be a challenge because of high junctional forces. Initial designs included one that used flanges that fit over the cortex as well as an intramedullary stem.\textsuperscript{24} The use of methyl methacrylate for cementation began when Charnley’s techniques for hip arthroplasty were adopted in the 1960s. Cemented stem designs included fluted, smooth, grit-blasted, and coated stems. In 1996, Unwin et al.\textsuperscript{25} described a series of cemented prostheses implanted between 1968 and 1993, including proximal femur replacements, with 90% survival at 5 years and 67% survival at 10 years. Additional modifications included a collared porous coating to improve bony and soft-tissue attachments at the proximal end of the stem (Figure 2).

Press-fit stems were developed to avoid the complications seen with cement, including midterm to late loosening problems. These stems have the potential for ingrowth and bony integration and therefore potentially better durability. The MUTARS (Modular Universal Tumour and Revision System; Implantcast) prosthesis, a press-fit system that uses a hexagonal
the prosthesis rather than through a claw or cables. Surgical techniques such as a slide osteotomy can be used to maintain the continuity of the abductors to the vastus lateralis and minimize disruption. Soft-tissue attachment can also be achieved with the use of allograft-prosthetic composite reconstruction, which uses the natural soft-tissue attachments to the proximal femur to reconstruct the abductors. The cost of these procedures is higher because they require both the implant and the bone allograft. Also, infection rates have been shown to be higher, likely as a result of the longer duration of the procedure. Other common problems include nonunion, resorption of the allograft, and loss of soft-tissue attachment to the trochanter.29

Various femoral head configurations have been used over the years. The general consensus has been to use unipolar or bipolar heads in younger patients to preserve acetabular bone stock. Unipolar or bipolar heads can also be used in older patients who may not survive long enough to wear out the acetabulum. These larger head sizes decrease the risk of dislocation. Other options to decrease the risk of dislocation include the use of a constrained acetabular cup or the use of an unconstrained prosthesis with capsular preservation and purse-string sutures around the femoral neck.30

Distal Femur

The distal femur is the most common site of primary bone tumors and a frequent site of metastatic tumors. One challenge in this location is that removing this segment of bone destroys the knee ligaments. To obtain durable function, the design of the prosthesis needs to balance stability with range of motion. Fixation of these reconstructions to the femoral stem presents challenges similar to those encountered in proximal femur endoprosthetic reconstruction, where a long lever arm is engaged with a diaphyseal segment of bone. The functional impact of the loss of muscular attachments is less substantial in the distal femur than in the proximal femur.

Bradish et al31 published one of the first series of distal femur replacements after the introduction of the Austin Moore prosthesis in 1952. They reported >40 distal femur replacements performed between 1964 and 1980 for the management of traumatic, locally aggressive, and malignant conditions. The first distal femur replacements in their series were fixed with extramedullary plates and were constructed with acrylic dental polymer. This design was replaced with one that used a cobalt-chromium-molybdenum alloy and fixation with integrally cast slotted plates. Bradish et al31 switched to intramedullary fixation in the 1960s, using cold-curing acrylic cement with metal prostheses created by Stanmore Implants and a fixed-hinge design. A substantial improvement in the 1970s was the introduction of high-density polyethylene for the bearing surface. Overall, Bradish et al31 reported 80% survival at 8 years. Other authors reported 10-year survival rates between 59% and 67%.32 Other design modifications in these series included an improved radius of curvature. The addition of medial and lateral flat faces, or flutes, was thought to prevent rotation and allow better fixation with cement.

In an attempt to move away from constrained hinge-type prostheses, other linkage techniques were developed. Overconstraint was suspected to lead to higher rates of aseptic loosening. Also, metal-on-metal debris generated with these early devices led to chronic effusions and may have contributed to loosening and infections. The designs that emerged allowed more motion in other planes. Examples include the Herbert knee prosthesis, which has since been pulled from the market, and the Spherocentric press-fit bone anchorage system, was described in 2006 with 5-year survival of 68.5% in the lower extremity.26

The most problematic aspect of proximal femur reconstruction devices is the loss of soft-tissue attachments. The inability to reattach the abductors can cause a Trendelenburg gait, a painful limp, and an increased incidence of dislocation. Without the iliopsoas, hip flexion strength is diminished. Leg extension and the ability to rise from a chair are compromised with the detachment of the gluteus maximus insertion. Various configurations of holes in the prosthesis have been used to attach the soft tissues.27 Aortograft has been used to improve the adhesion of soft tissues to a sleeve around the graft with good results.28 Some designs include the option of a trochanteric bolt, which allows a trochanteric slide osteotomy to be connected directly to
knee prosthesis (Howmedica), which used a captured ball-and-socket design. These devices, however, still had relatively high rates of loosening, revision surgery, and infection. The kinematic rotating hinge prosthesis (Howmedica) added rotational motion to the tibia to reduce stresses but had increased incidences of shaft perforation and patella dislocation. This prosthesis was followed by the Noiles knee (Joint Medical Products), which had a similar design.

Subsequent improvements included deepening and lateralizing the trochlear groove, making the distal femur component smaller, using thicker stems, developing new coating surfaces for press-fit implants to avoid the use of cement, introducing more wear-resistant polyethylene, and using a modular implant system for ease of use.1 The GMRS (Global Modular Replacement System; Stryker) prosthesis demonstrated an estimated survival rate of 66% at 5 years and 58% at 8 years in one study, with the most common mode of failure being infection.32 Authors using the MUTARS prosthesis, a competing system, found lower rates of aseptic loosening with hydroxyapatite-coated noncemented stems than with uncoated noncemented stems33 (Figure 3).

The use of megaprostheses for limb salvage in pediatric patients with lesions around the distal femur is a particularly difficult task because of the small size of the skeleton, the risk of limb-length discrepancy, and the activity level of this population. Historically, for most pediatric patients, the preferred options have been amputation, allograft reconstruction, or rotationplasty. If the child is close to skeletal maturity, a megaprosthesi can be used with or without contralateral epiphysiodesis. Expandable designs have been created to compensate for the loss of growth resulting from growth plate sacrifice after excision of the distal femur and proximal tibia in pediatric patients. One of the largest early series, beginning in 1976, used four different mechanisms of expansion.34 These prostheses were manufactured from titanium alloy for the shaft and stem and cobalt-chromium for the knee hinge, total femur, and proximal tibia components, with a fixed-hinge device for the knee. The expansion mechanisms included a worm drive, a ball bearing inserted in a passive extender, a C-clamp mechanism, and, in later prostheses, a minimally invasive worm drive that could be operated with a small screwdriver. Complications include aseptic loosening, fixed flexion deformity at the knee, pain, infection, limb-length discrepancy, and jamming of the expansion device.

A rotating platform design was added to decrease aseptic loosening rates. An example of this design is the Finn knee (Zimmer Biomet) prosthesis, with a screwdriver-driven worm mechanism for expansion and a smooth metal tibial component to allow for continued growth of the tibial epiphysis.35 Revision rates have ranged from 20% to 77%. In 2002, the Repiphysis system (Wright Medical Technology) was approved in the United States. This system used electromagnetic fields for prosthesis lengthening to avoid the need for invasive procedures. In an early case series, all patients had good function, and none had aseptic loosening.36 Other reports were less favorable. One group studied 10 pediatric patients at 2-year follow-up, with 37 reported implant-related complications.37 The most common modality of failure was aseptic loosening. Other researchers reported failure of spring deployment, spontaneous spring deployment, and implant body failures.34,36 Further advancements in expandable implant designs included the JTS design (Stanmore Implants), which uses a magnet and gearbox, and the Xpand and BioXpand devices (Implantcast), which use a receiver for high-frequency transmission that drives expansion of the prosthesis in the former device and distraction osteogenesis of the bone over the stem in the latter.

Total Femur

The goal of total femur reconstruction is to implant a device that replaces the form and function of the entire femur. The main advantage of total femur reconstruction is the early mobilization and full weight bearing that it affords. Functional outcomes depend on femoral anteversion, patellar...
tracking, restoration of limb length, quality of soft-tissue healing, and attachment of the soft-tissue abductor musculature. Patellar tracking can be optimized with adequate tension of the extensor mechanism and rotation of the femoral and tibial components, avoiding internal rotation. Improvement of alignment can be attained with lateral retinacular release with or without medial retinacular imbrication. Failure of these devices can be catastrophic because their use requires the removal of a substantial amount of tissue.

These prostheses have improved as a result of improvements in the designs of the proximal femur, the distal femur, and the linkages on both ends. The use of total femur replacements dates from 1965, when Buchman reports on a total femur and knee replacement with a custom-made Vitallium endoprosthes. This prosthesis, and others similar to it, simply replaced the entire femur with a cobalt-chromium monoblock implant with no linkage to the stem of either the hip or knee prosthesis component, thereby avoiding the problems of cementation, fracture, and aseptic loosening. Since then, the prostheses used in total femur replacements have evolved from custom designs to modular constructs.

Total femur endoprosthesis designs can be categorized into two main types. One is the intramedullary total femur replacement. This design consists of a custom-made intercalary sleeve that links a well-fixed hip stem with the stem of a total knee arthroplasty prosthesis. Because of its small diameter, this design allows for preservation of bone stock and soft-tissue attachments. The risk of this design is that it has weaker linkages and is not as mechanically strong as the second type of total femur endoprosthesis. The second category, known as the oncologic endoprosthesis, consists of an intercalary metal segment that connects to total hip and knee arthroplasty prostheses through preimpacted Morse tapers. Jones et al reported on patient-oriented functional outcomes in patients who underwent total femoral endoprosthetic reconstruction after oncologic resection. In their series, the authors found worse function with total femur reconstruction than with proximal femur reconstruction or distal femur reconstruction at 4-year follow-up. Conversely, other reports have demonstrated improved function in patients with total femur reconstruction after multiple failed revision proximal femur or distal femur reconstructions. Infection is one of the largest problems with total femoral replacements, independent of their design. Factors associated with infection include extensive surgical resection, large metal surfaces, prolonged surgical time, multiple patient comorbidities, and repeated hospitalizations.

Proximal Tibia

The proximal tibia is the second most common site of primary malignant bone tumors after the distal femur but historically has been the most common location of prosthesis failure. The primary challenges in reconstruction of this bone involve the patellar tendon, the limited soft tissues covering the proximal tibia, fixation into a short segment of the tibia, and linkage to the knee. An additional difficulty arises from the intimate relationship of the proximal tibia to the nerves and blood vessels. Because of these issues, most surgeons in the early development of tumor surgery chose resection arthrodesis and above-knee amputation over reconstruction. When limb salvage was considered, allograft and allograft-prosthetic composite historically were the primary choices.

In 1979, Sim and Chao reported on three patients who underwent tibial resection and reconstruction with a custom megaprosthesis. Methyl methacrylate was used for fixation, and a hinged knee prosthesis with no rotating platform was used for reconstruction. Horowitz et al reported on their experience in 1991. All 16 patients had primary sarcoma of the proximal tibia and underwent extra-articular resection and reconstruction with different types of megaprostheses, with a constrained titanium ball-and-socket articulation between the femoral and tibial implants and fixation with cemented stems. Aseptic loosening was seen in 3 of 11 patients available for follow-up; substantial extensor lag was seen in all 11 patients, even those who underwent reconstruction of the extensor mechanism. In a different study, the technique used to repair the extensor mechanism, consisting of Dacron tape applied over autologous bone graft to a porous-coated...
prosthesis, or a medial gastrocnemius flap sutured to the patella tendon and quadriceps muscle, was shown to be effective.\textsuperscript{44} Extension lag of $<20°$ to full extension was seen in 44 of 55 patients in this study. A recent report highlighted a 25-year series of reconstructions with overall prosthesis survival of 82\% at 5 years and 78\% at 10 years.\textsuperscript{45} Extensor mechanism reconstruction techniques used in this series included attachment with nonabsorbable sutures with or without a flap, mechanical clamping, and use of a polyethylene plate, with the best function reported in patients who underwent direct attachment of the extensor mechanism to the prosthesis with an artificial tendon and a medial gastrocnemius flap.

One of the main challenges in reconstruction of the proximal tibia is the attachment of the patellar tendon. Allograft-prosthetic composites can be an option to address this challenge. The disadvantages of this method are the increased cost and infection rate. Soft-tissue coverage can be more difficult with allograft-prosthetic composites because megaprostheses can be designed to be smaller, whereas the combination of the allograft, the prosthesis, and the stabilizing plate that is often used can make the construct bulky.\textsuperscript{46} A recent review comparing allograft-prosthetic composites with megaprostheses highlighted a 93\% 10-year survival rate of allograft-prosthetic composites versus 78.8\% for megaprostheses, with improved function of the extensor mechanism in the former\textsuperscript{46} (Figure 5).

**Future Directions**

Over the years, the demands on megaprostheses have increased. The life span and prognosis of patients with metastatic disease are slowly improving. Patients with sarcomas are testing their reconstructions as never before, as they go on to live long lives after undergoing treatment and excision of their sarcomas. The greatest advancements in the future will likely address the most challenging problems related to the use of megaprostheses, such as preventing infection, improving soft-tissue attachments, and improving the durability of the bone-prosthesis interface.

Emerging technologies have the potential to address these problems. Three-dimensional printing, in the form of laser additive manufacturing for construction of metal prostheses, and other techniques provide novel methods for production of custom devices in the span of hours, whereas production used to take weeks.\textsuperscript{47-49} The quick turnaround will allow for greater experimentation with device features and adaptation to patient-specific anatomy and problems. The application of nanotechnology in megaprostheses has the potential to prevent infection, improve soft-tissue attachments, and improve the durability of the bone-prosthesis interface. Novel surfaces can prevent biofilm formation, attract soft-tissue attachment, and allow bony ingrowth. The next generation of megaprostheses may be made of different materials that allow for resorption or controlled integration into the body. Although metal has been useful because of its durability and ease of manufacturing, it is recognized as foreign by the body, does not allow for adequate vascularity to clear infections, and does not integrate into the body to replace all necessary lost function. Megaprostheses developed in the future may have added functionality built in, including elements such as drug delivery devices. These prostheses could incorporate smart technologies, such as sensors for early detection of infection or tumor recurrence. Future megaprostheses may include parts that replace not only bone but also soft tissues, such as muscles and tendons. Other megaprosthetic reconstructions may incorporate attachment devices that have already been applied in primary reconstructions in patients with limited bone stock and in revision scenarios, such as the Compress Device (Zimmer Biomet), which increases the strength of the bone-implant connection over a short segment of bone.

**Summary**

The use of megaprostheses to restore the form and function of a removed large segment of bone will likely to continue to improve, with future developments improving the quality of life of oncologic and nononcologic patients. Compared with early devices, current megaprostheses have been shown to be a reliable option to address challenging problems in the right patient.
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References

Evidence-based Medicine: Levels of evidence are described in the table of contents. In this article, reference 27 is a level II study. References 1, 2, 18-20, 25, 26, 32, 33, 39, 45, and 46 are level III studies. References 3-17, 18-20, 25, 26, 32, 33, 39, 45, and 46 are level IV studies. References 24 and 47 are level V expert opinion.

References printed in bold type are those published within the past 5 years.


