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Review of Endoprosthetic Reconstruction in Limb-sparing Surgery

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OVERVIEW

Endoprosthetic replacement of segmental skeletal defects is the preferred technique of reconstruction after resection of bone sarcomas. Today, all of the major anatomic joints with their adjacent segmental bone can be reconstructed safely and reliabily with a modular endoprosthetic replacement. Prosthetic reconstruction is routinely performed for the proximal femur, distal femur, total femur, proximal tibia, proximal humerus, and scapula. Allografts are rarely used.

A major advantage of a modular endoprosthetic system is intraoperative flexibility; it enables the surgeon to reconstruct defects of any size with minimal preoperative planning. Instead of performing a resection to match a prosthesis customized on the basis of imaging studies that are 4–8 weeks old, the surgeon can concentrate on performing the best possible resection indicated for the patient at the time of surgery. Overall survival analyss of large segmental replacements is approximately 90% at 10 years (reported at 98% for the proximal humerus and 90% for the distal femur).

This chapter reviews the indications and techniques for performing endoprosthetic replacements for bone tumors. Many of the described surgical techniques were developed by the senior author, placing emphasis on techniques for reconstructing the soft tissues after implantation of a modular endoprosthesis to optimize the functional outcome.

INTRODUCTION

The concept of limb-sparing surgery, or limb salvage, has gradually evolved over the past 25 years. Prior to this the basic principles of surgical oncology for the extremities consisted solely of determining the correct level at which to perform an amputation. With the introduction of effective Adriamycin- and methotrexate-based chemotherapy protocols in the early 1970s at centers such as Memorial–Sloan Kettering, New York University, and the Children's Hospital of Philadelphia, surgeons such as Ralph Marcove, Kenneth Francis, and Hugh Watts developed techniques of limb-sparing surgery. Today, 90–95% of patients with extremity sarcomas who are treated at major centers specializing in musculoskeletal oncology can undergo successful limb-sparing procedures.

This dramatic alteration in patient care is the result of significant advances along many fronts, including:

1. improved understanding of tumor biology;
2. effective induction chemotherapy;
3. technical advances in surgical techniques;
4. better characterization of the biomechanics of the human skeleton;
5. advanced material engineering and manufacturing techniques;
6. the development of a reliable, stable modular prosthesis for reconstruction of the hip, shoulder, and knee.

This book focuses primarily on techniques of oncologic resection that have been developed by the authors over the past 20 years. Emphasis is placed on several principles that are key to the success of this technique. The first is identification and preservation of key neurologic and vascular structures in the limbs and pelvis. Second, the importance of achieving an appropriate oncologic margin cannot be overstated, for preservation of the limb should rarely, if ever, take precedence over the survival of the patient. Achieving safe margins requires meticulous surgical technique. Resection, however, is only the first stage of a limb-sparing procedure. Reconstruction of the axial skeleton and restoration of soft-tissue coverage for optimal function are also performed.

The purpose of Chapter 25 is to review the major medical and surgical considerations in selecting a patient for limb salvage and to discuss the options available for reconstructing the defect remaining after an oncologic resection. An overview of the surgical techniques for reconstruction of each major joint, as developed and currently practiced by the authors, is presented.

PATIENT SELECTION

Appropriate patient selection for limb-sparing procedures is essential to ensure good, consistent results. Although the introduction of chemotherapy for osteosarcoma was a major impetus for the development of techniques for limb-sparing surgery, increasingly high long-term survival rates have placed greater emphasis on the functional outcome and longevity of the reconstruction. Today's patient expects a solution that addresses his or her functional, cosmetic, and psychological needs.

The location and involvement of critical anatomic structures are often the determining factors in selecting patients for limb salvage versus a primary amputation. With the use of modern neoadjuvant (i.e. preoperative, induction) chemotherapy, many patients who are initially not suited for a limb-sparing procedure may ultimately become candidates for such surgery. Therefore, the final surgical decision is often not made until a patient has been re-evaluated following the completion of neoadjuvant treatment. Improvements in chemotherapy have increased the pool of patients amenable to limb-sparing procedures.

Limb-sparing procedures, moreover, are not necessarily limited to patients who respond to treatment. Patients with very poor prognostic factors, such as those with metastatic disease upon initial presentation and those who fail to respond to chemotherapy, often require significant palliative surgery in order to maintain an acceptable quality of life. Because these individuals have a limited life expectancy, amputation should be avoided in all but the extreme cases who require emergency palliation. Radical or mutilating procedures are not appropriate for patients if there is no hope of prolonging their survival. The surgical intervention selected is dependent on where a given patient falls within the spectrum of potential oncologic outcomes.

ROLE OF IMAGING STUDIES AND PATIENT STAGING

Advanced imaging modalities have vastly improved our ability to accurately determine the extent of tumor prior to surgical exploration. High-resolution axial and multiplanar images from computerized tomography (CT) or magnetic resonance imaging (MRI) scans can determine the extent of the tumor and its relationship to the surrounding anatomic compartments. CT imaging of the chest is performed to detect pulmonary metastases, and technetium bone scanning of the entire skeleton is performed to detect the presence of metastatic disease. For bone sarcomas, and most soft-

tissue sarcomas, the lungs and skeleton account for the vast majority of all sites for metastases. High-quality imaging studies, combined with detailed histologic grading of a biopsy (preferably done by a core needle), allows for accurate staging.

Early attempts to stratify patients on the basis of tumor size failed to account for the biologic behavior of a given tumor. A more reliable approach is a staging scheme that accommodates the fact that the aggressive nature of a tumor can be graded by the histologic appearance of the cells and their nuclei. William Enneking[1] added to this the concept of an anatomic compartment, which acts as a relative barrier to tumor spread. His staging system combined tumor grade and anatomic extent in a simple, yet easily reproducible and prognostically significant format. The Musculoskeletal Tumor Society has adopted this system as its preferred method for staging extremity sarcomas.

Limb salvage for Stage I (low-grade) and Stage IIA (high-grade, intracompartmental) lesions is now routinely performed, because these tumors are easily resectable. A majority of the surrounding soft tissue can routinely be preserved. For these patients, reconstruction is typically limited to restoration of skeletal stability. Stage IIB tumors, which can involve multiple compartments, may be unresectable at presentation. Neoadjuvant chemotherapy can have a dramatic role in converting patients with tumors that are initially thought to be unresectable into candidates for limb-sparing surgery. Such a conversion may occur when chemotherapy causes the tumor to shrink, thereby freeing critical neurovascular structures. Finally, patients with Stage III disease may be considered for palliative resections in lieu of amputation, provided that prolonged immobilization or delayed wound healing does not interfere with their medical treatment. In patients with Stage IIB and III tumors, skeletal and soft-tissue reconstruction must be performed.

STAGES OF LIMB-SPARING SURGERY

A successful limb-sparing procedure can be divided into three stages, each of which directly affects patient outcome and survival. First and foremost, tumor resection must spare significant structures. Second, a stable, painless skeletal reconstruction must be accomplished. Third, the surrounding and supporting soft tissue is required to restore function and skeletal reconstruction.

As the techniques of surgical resection have been refined, the number of patients that fulfill these categories has increased. For example, involvement of a major vascular bundle formerly mandated an amputation. Today, major vessels are routinely resected en-bloc with the tumor; this is followed by vascular reconstruction utilizing an artificial graft or reversed vein graft. Likewise, use of local rotational pedicle flaps or microvascular free flaps allows for reconstruction of patients whose tumor resection necessitated removal of significant portions of the surrounding soft tissue. Such flaps provide the muscle and skin coverage necessary to restore limb function and prevent postoperative periprosthetic infections.

RECONSTRUCTIVE OPTIONS FOR SKELETAL DEFECTS

There are four major methods of reconstructing a skeletal defect. These are as follows:

1. *Resection arthrodesis*. Prior to the routine use of chemotherapy in the 1970s, resection of a sarcoma entailed the loss of significant amounts of muscle. Little tissue was left for functional reconstruction. In these early days of limb salvage, resection arthrodesis was the main method of reconstruction. (Figure 25.1) Its primary advantages were to restore skeletal stability and produce a long-term, durable reconstruction. No attempt was made to restore motion at the resected joint, however, and many patients expressed dissatisfaction with their loss of function. Today, effective chemotherapy allows for the preservation of significant functional muscle groups, and the use of rotational flaps can restore function when muscle is lost. As a result, resection arthrodesis is rarely recommended as the primary method of reconstruction today; in fact, a number of long-term survivors originally treated with arthrodeses around the knee have undergone conversion to endoprosthetic reconstruction to restore their ability to passively flex and extend the knee.
2. *Osteoarticular or massive allografts*. Allograft reconstruction was championed in the 1970s as a biologic solution to the problem of restoring a segmental defect of the skeleton. Despite technical improvements in the method of fixation, and in the processing of the allograft to preserve cartilage cells and reduce contaminants, this method of reconstruction has significant complications. These include early complications, such as infection, nonunion and joint instability, and late complications such as instability and allograft fracture. Overall complication rates can exceed 50%, including an infection rate of 30%, even when performed at a major center.[2] As a result, allograft procedures are preferred at only a few centers today. Many surgeons avoid them entirely in patients undergoing chemotherapy for high-grade sarcomas.

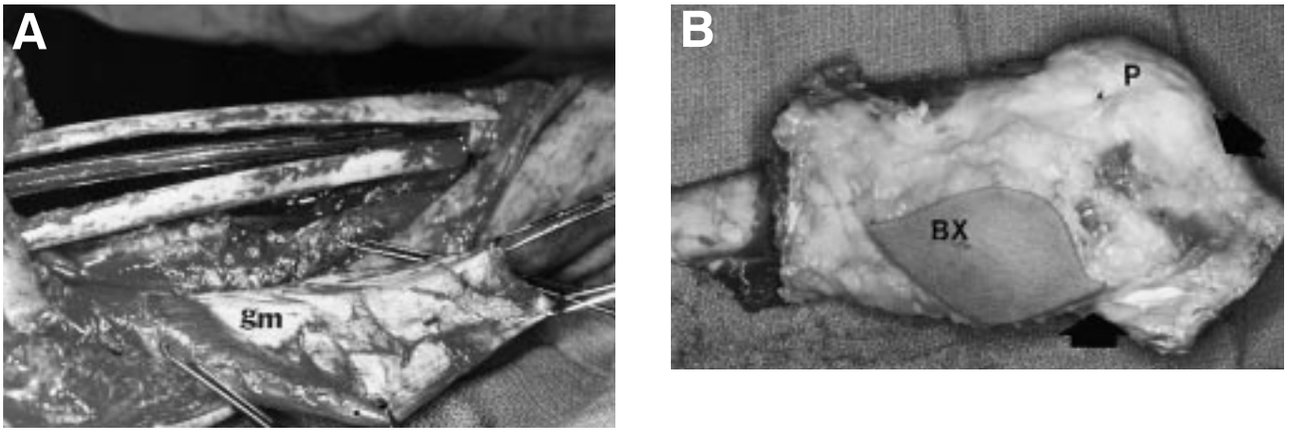


Figure 25.1 Resection arthrodesis (per Enneking). (**A**) Intraoperative photograph demonstrating the dual fibular reconstruction with an intramedullary rod fixation following resection of the distal femur. This technique of reconstruction was popularized during the 1970s by Dr William F. Enneking prior to the development of reliable reconstruction prostheses. Note the medial gastrocnemius flap (gm) has been mobilized for rotation closure of the defect. (**B**) Gross specimen following an extra-articular resection of the distal femur. Note the biopsy tract was removed with the specimen. The arrows indicate the level of the joint. This was the standard technique for resection during the 1970s and early 1980s. Today this technique is rarely performed.

Currently, we perform allograft reconstruction for the rare patient with a diaphyseal lesion that can be reconstructed with an intercalary allograft or for very young patients who might be expected to develop substantial leg-length discrepancies as they grow. For the latter patients an allograft can preserve additional growth plates and reduce the expected leg-length discrepancy. Ultimately, such patients often require conversion to an endoprosthesis because their functional demands result in fracture of the allograft.

3. *Endoprosthesis.* Endoprosthetic reconstruction is a highly successful and durable method for the restoration of skeletal integrity and joint function. Use of a cemented stem provides immediate fixation, which allows for early mobilization and rehabilitation. Extensive experience in joint replacement has led to the development of materials suited for long-term prosthetic survival; at the same time, advances in the use of local rotational flaps have improved joint stability and simultaneously reduced the risk of infection. Since the mid-1980s custom-manufactured endoprostheses have been replaced by modular systems with standard instrumentation that vastly expands the reconstruction options (Figure 25.2). This is the authors' preferred method of reconstruction and this chapter will expand on the topic, below.
4. *Allograft–prosthetic composite (APC).* APCs can be viewed as a transitional step between allografts and endoprostheses. This procedure became popular when surgeons began to abandon pure osteoarticular allografts. APCs were thought to provide the benefits of a biologic reconstruction along with the immediate stability achieved by a cemented endoprosthesis. Experience has shown that this method has the same high rate of early complications (i.e. infection and nonunion) as does standard allograft reconstruction. Accordingly, this method is better suited for a patient undergoing revision of a failed allograft, rather than a patient undergoing chemotherapy for a sarcoma.[3]

HISTORY OF ENDOPROSTHETIC RECONSTRUCTION

The earliest published example of an endoprosthetic reconstruction following treatment of a bone tumor dates to 1940, when Austin Moore and Harold Bohlman implanted a vitallium proximal femur in a patient with a giant-cell tumor. In the early 1970s Kenneth Francis and Ralph Marcove ushered in the current age of endoprosthetic reconstruction following radical resection of osteosarcomas by developing a distal femoral and a total femoral replacement, respectively (Figure 25.3).[4]

This new concept of limb-sparing surgery for sarcoma patients was based on the hope that Adriamycin and methotrexate, newly introduced for osteosarcoma in the early 1970s, would permit a safe limb-sparing resection in lieu of primary amputation. However, it was soon recognized that the 6–8 week lag time between diagnosis and the creation of a custom

Figure 25.2 Types of distal femoral replacements. (**A**) Anterior–posterior view. (**B**) Lateral view. A = initial custom prosthesis used between 1981 and 1985; B = similar prosthesis with porous coating adjacent to the stem (arrow) to permit intracortical bone fixation: this prosthesis was first used in 1985; C = Modular prosthesis (Howmedica, Inc., Allendale, NJ) initially used in 1988 (see text). The modular design is presently used for most anatomic sites.

endoprosthesis for a given patient could have a negative impact on survival. As a result, Gerry Rosen and Ralph Marcove invented the concept of induction (i.e. preoperative or neoadjuvant) chemotherapy, according to which patients with osteosarcomas received chemotherapy during the interval from time of diagnosis of the tumor to the delivery of that patient's custom implant.[4] Induction chemotherapy is now administered to patients with a wide variety of cancers.

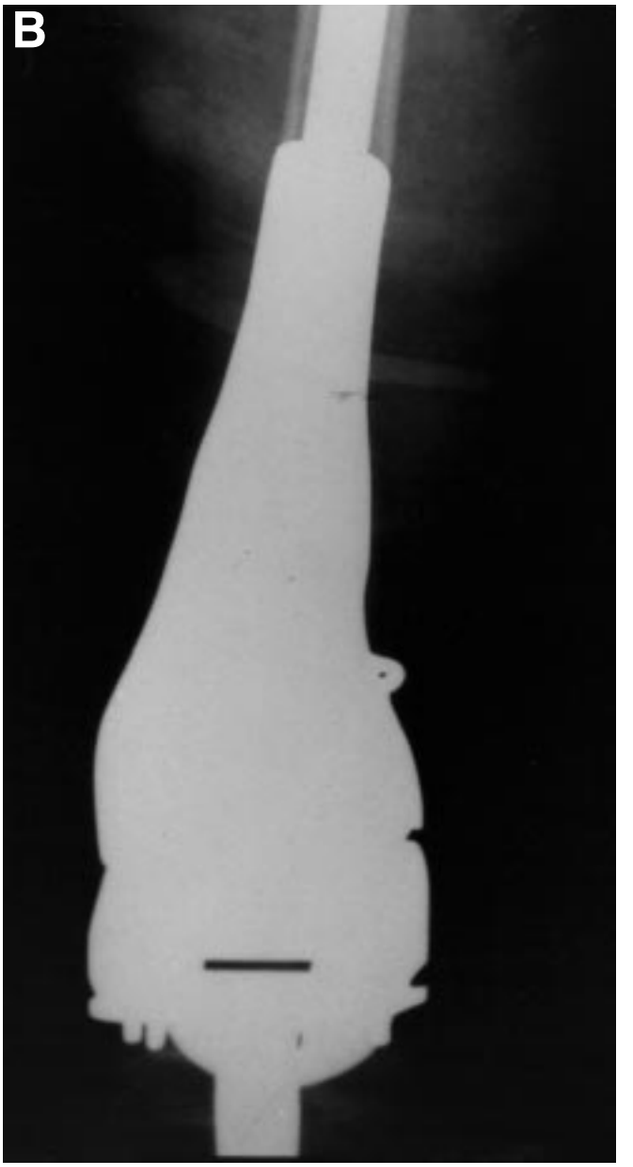
Specific examples of endoprosthetic reconstructions, that will be discussed in detail in this chapter, include the following:

Hip (Proximal Femur, Saddle)

Tumors involving the proximal femur, which include both primary sarcomas and metastatic carcinomas, are extremely common. Following resection of a primary tumor or fracture through a subtrochanteric metastatic lesion, the proximal femur can be readily replaced. Typically, a bipolar hemiarthroplasty is used for the hip joint with reconstruction of the hip capsule to prevent complications related to postoperative dislocation. Hip abductors can be reconstructed by attaching them directly to the prosthesis via a laterally placed metal loop. Much less common are resections of the entire hip joint (type II pelvic resection and its modifications). This defect can be reconstructed with a saddle prosthesis, a device that derives its name from the U-shaped component that articulates with the remaining iliac wing. Stability is achieved by balancing the muscle tension between the medial iliopsoas and the lateral hip abductors.

Knee (Distal Femur) (Figure 25.4)

The distal femur is the most common site for primary bone sarcomas. Prosthetic reconstruction requires a unique combination of flexibility and stability, because the knee capsule and the cruciate and collateral ligaments are removed during the resection. The rotating hinge design permits both flexion and extension, as well as rotation through the knee, while maintaining stability in varus/valgus and anterior/posterior planes.



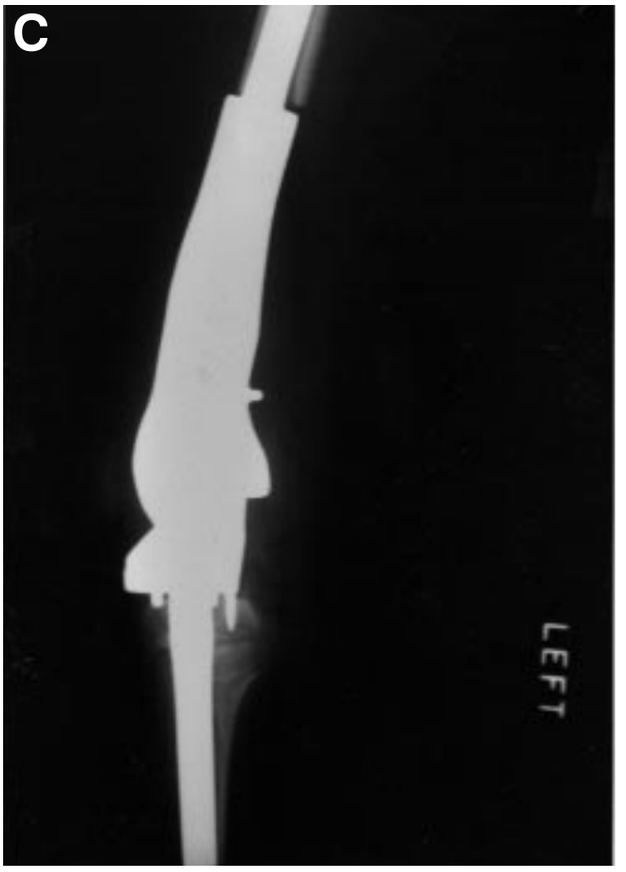


Figure 25.3 Photographs of the first distal femoral replacement performed in the United States by Dr Kenneth Francis at New York University in 1973. (**A**) Plain radiograph of a large Stage IIB osteosarcoma. This patient was treated with Adriamycin alone, which was the only available active sarcoma drug at that time. (**B**) Anterior–posterior photograph of the distal femoral replacement utilized. Note the long femoral and tibial stems. Polymethylmethacrylate was utilized for fixation. The knee component was a modified Walldius fixed knee hinge. (**C**) Lateral photograph of the same prosthesis. Note the long tibial stem and spikes for fixation.

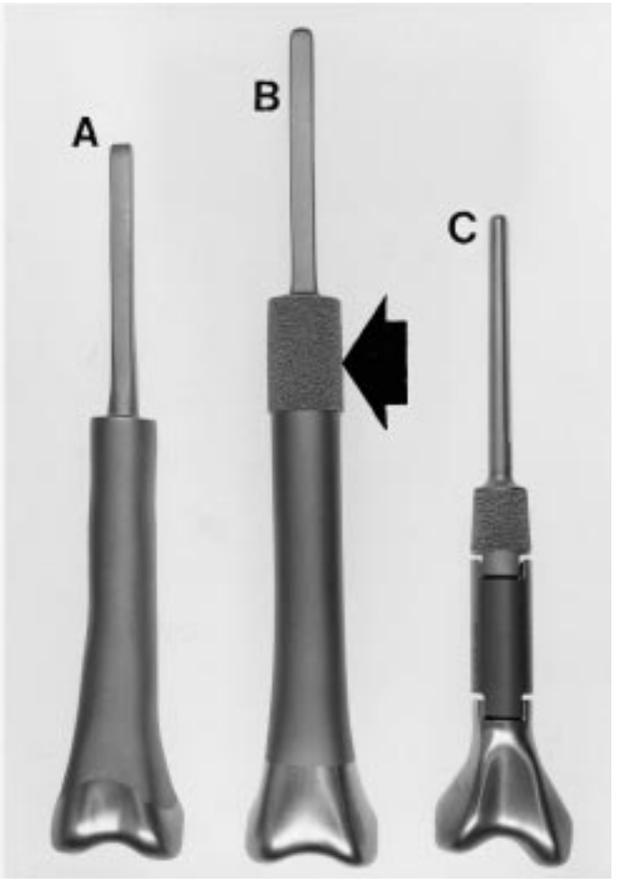


Figure 25.4 Custom distal femoral prostheses used between 1982 and 2000. (Knee component not shown) (**A**) Original custom prosthesis (1982). (**B**) Custom prosthesis (1984–1988) with porous collar (solid arrow) to permit extracortical bone fixation and soft tissue attachments (1984–1988). (**C**) Modular segmental prosthesis. This was the original segmental design (1988) which is currently in use today with some modifications (Courtesy Howmedica Inc., Rutherford, NJ).

Reconstruction of the extensor mechanism is rarely required since the patella can usually be saved during the resection.

Total Femur

Patients presenting with the rare sarcoma that has an extensive intramedullary extent, as well as patients with multiply failed total joints and little remaining bone stock, can be treated with a total femoral replacement. A natural combination of the distal femoral rotating hinge and the proximal femoral replacement with a bipolar head, this type of reconstruction has proven to be extremely durable as a result of the degrees of freedom that are afforded by the two separate, but related, joints.

Proximal Tibia

The tibia is unique given its subcutaneous border along the anterior leg. Any form of reconstruction can be jeopardized by even minimal amounts of skin necrosis. Routine use of a gastrocnemius rotation flap has dramatically reduced the incidence of postoperative complications. Joint stability at the knee is assured by using the same rotating hinge design used for distal femoral replacements.

Shoulder (Proximal Humerus)

High-grade sarcomas of the proximal humerus require extra-articular resection, that includes the entire rotator cuff and deltoid muscles. The functional outcome of a proximal humeral replacement following this type of resection is therefore greatly restricted by lack of functional muscle. A combination of static and dynamic suspension, including transfer of the pectoralis muscle, stabilizes the proximal humerus to the scapula, and permits painless and functional use of the elbow, wrist, and hand.

Scapula (Scapulohumeral)

Following total resection of the scapula, a scapular prosthesis helps lateralize the humerus and stabilize the shoulder joint. Resurfacing the humeral head and reconstruction of the capsule with a Dacron graft is necessary for optimal stability. Functional outcome depends on the amount of muscle preserved during resection.

Elbow

The elbow joint is rarely involved by sarcomas or metastatic disease. Customized, hinged implants with small-caliber stems to fit the ulna and distal humeral canals may be used, provided that sufficient soft tissue remains to cover the prosthesis.

Total Humerus

This implant is a combination of a proximal humeral implant and an elbow replacement. The indications for this procedure are rare, but a sensate, functional hand remains preferable to an amputation.

Calcaneus

There has been one reported case of a total calcaneal prosthesis implanted in lieu of a below-knee amputation in a patient with osteosarcoma. Five years after surgery this patient is fully ambulatory and does not depend on assistive devices.

Expandable Implants for the Skeletally Immature Patient

Reconstruction of the axial skeleton in immature patients is problematic. Children over the age of 10–12 years can often be treated as adults, using smaller versions of the modular prostheses, occasionally in combination with contralateral epiphyseodesis to equalize leg length at skeletal maturity. Below the age of 6, primary amputation remains the preferred method of tumor resection, given the extraordinary difficulty in obtaining a proper oncologic margin around the critical neurovascular bundles. In children between the ages of 6 and 10–12 reconstruction is feasible, but limb-length inequality becomes functionally disabling as the child grows. Implants that can be expanded multiple times during growth permit prosthetic reconstruction for these children. These custom-created implants have been used both in the upper and lower extremities with mixed results. Mechanical failures of the expansion mechanism are not uncommon (see Figure 25.10, arrows). Many patients must undergo as many as 10 operative procedures to ensure limb equalization during the period of active growth.

As experience with prosthetic design and implantation grew, a wide variety of custom implants became available (Figure 25.2). All of the early prostheses, however, were individually designed and manufactured on a one-off basis. Prosthetic failures related to design flaws and errors in manufacturing were common. Improved design concepts and manufacturing techniques developed during the production of standard total hip and total knee prostheses were eventually applied to these "mega" prostheses (Figure 25.4). However, design improvements requiring increasingly complex mechanical geometry, and the increasing use of difficult-to-process alloys such as titanium and cobalt chrome, have lengthened the manufacturing time. These considerations offset the gains associated with long experience in handling custom implants and the reduced time needed to design the actual implant. As a result the minimum time between design and delivery of a sterilized custom endoprosthesis remains 6–12 weeks.

Endoprosthetic reconstruction is associated both with mechanical failures (e.g. stem fracture, erosion and failure of polyethylene components) and nonmechanical failures (e.g. infection and aseptic loosening). Advances in design and surgical techniques have reduced these problems substantially. However, the problem unique to custom endoprosthetic implants that cannot be controlled for is that the planned resection may need to be revised at the time of surgery. This is particularly true when the tumor grows significantly during the time that the prosthesis is being manufactured, or when there is a difference in the preoperative imaging measurements and the actual dimensions of the patient's bony anatomy or size of the tumor. Attempts to use a component that is not the appropriate size can significantly jeopardize the oncologic result, the functional result, or both.

Flexibility at the time of surgical reconstruction can be increased by incorporating modular features into the prosthesis (Figure 25.5). Although modularity increases the complexity of the mechanical construct, and carries with it risk of failure associated with the sum of all of the components, it has several significant benefits. The primary advantage is flexibility: the surgeon can concentrate on performing the best-possible oncologic resection knowing that any changes in the preoperative plan can be accommodated by having at hand the components needed to reconstruct the actual skeletal defect. The use of standard components also allows the surgeon to articulate trial components during the procedure, and to repeatedly modify and test a reconstruction before selecting and assembling the final prosthesis. Standardization of components also permits the implant manufacturer to greatly increase the level of quality control while reducing the cost of manufacturing through economies of scale. Modular systems can also reduce the overall inventory needed to provide a large choice of prosthetic shapes and sizes. Finally, a modular system lends itself to reconstructive situations outside of oncologic resections immediately available as a backup option for selected patients, such as those undergoing difficult joint revision surgery.

The Howmedica Modular Replacement System (HMRS, Howmedica International) designed and manufactured in Europe, was a first-generation modular endoprosthetic system. It featured intramedullary, cementless, press-fit stems supported by external flanges and cortical transfixation screws. The knee mechanism consisted of a simple hinge design. Significant problems encountered with this device included aseptic stem loosening (osteolysis), substantial stress shielding with bone resorption, screw fracture and migration, and a greater than 40% polyethylene failure rate for the knee mechanism.[5] As a result this system has rarely been used in the United States.

A second-generation limited modular system from Europe currently available in the United States is the

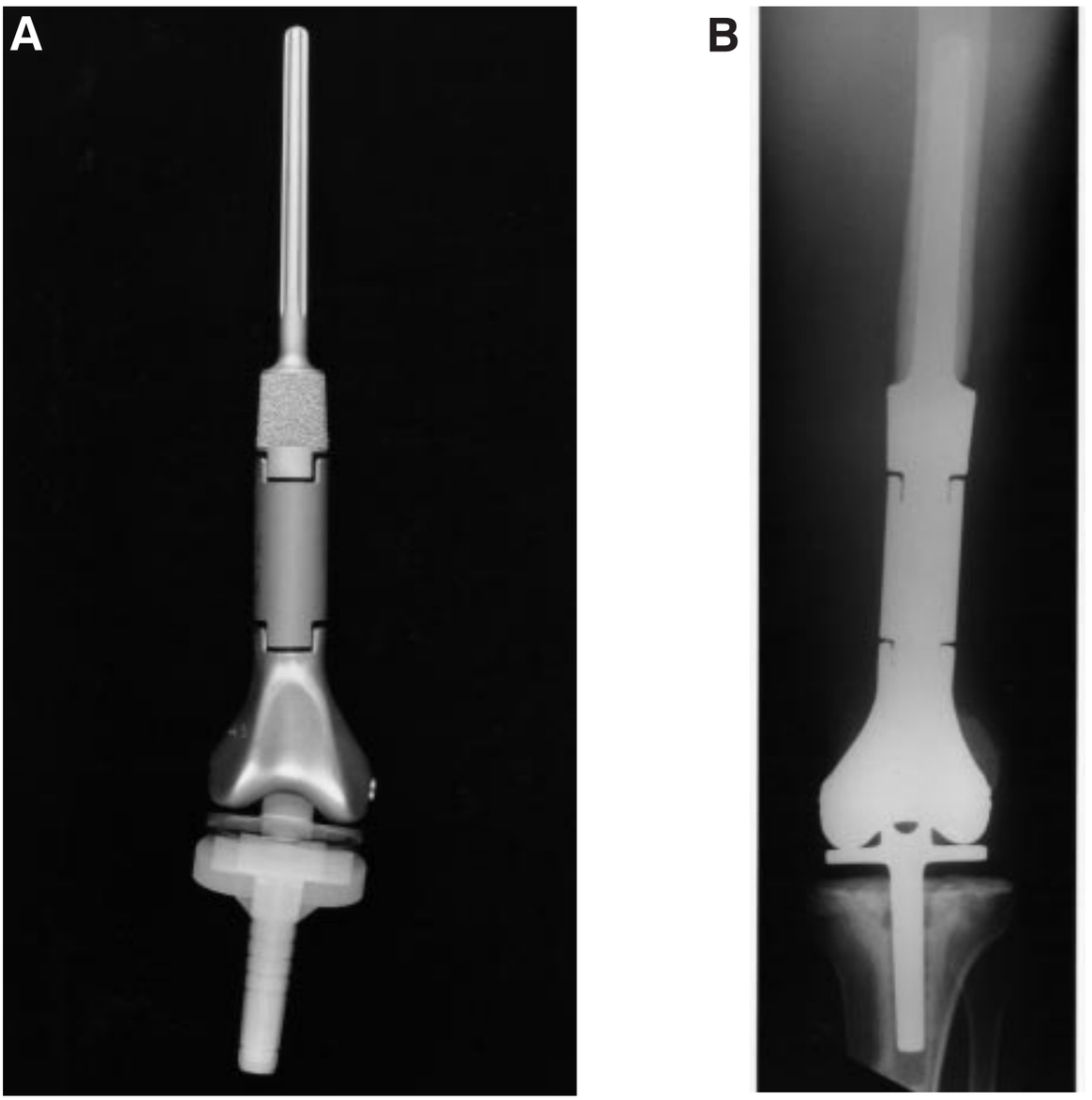


Figure 25.5 *(see also following page)* Modular replacement system (Howmedica, Inc.). (**A**) A distal femoral Modular Replacement System showing the stem, body, and condyles with the tibial insert (polyethylene) in which a tibial bearing plug (metal) is inserted. (**B**) Anterior-posterior photograph showing a distal femoral Modular Replacement System prosthesis in place. (**C**) Multi-phase photograph of the distal femur and proximal tibial component that demonstrates the range of flexion that is permitted with the kinematic rotating hinge knee component. (**D**) Multi-phase photograph of the distal femoral modular replacement showing the rotation that is permitted within the tibial bearing component. Note, there is almost a complete freedom of rotation. In order to control this rotation, good muscle reconstruction is essential.

modular saddle endoprosthesis (Link America, Denville, New Jersey). This prosthesis, designed for the treatment of infected, failed total hip replacements, has been modified to allow for reconstruction of the hip following resection of the pelvis. The unique feature of this system is the saddle, which is a U-shaped component that straddles the ilium, allowing motion in flexion/extension, and abduction/adduction by rocking in the AP and lateral planes against the bone. An additional ring containing polyethylene permits

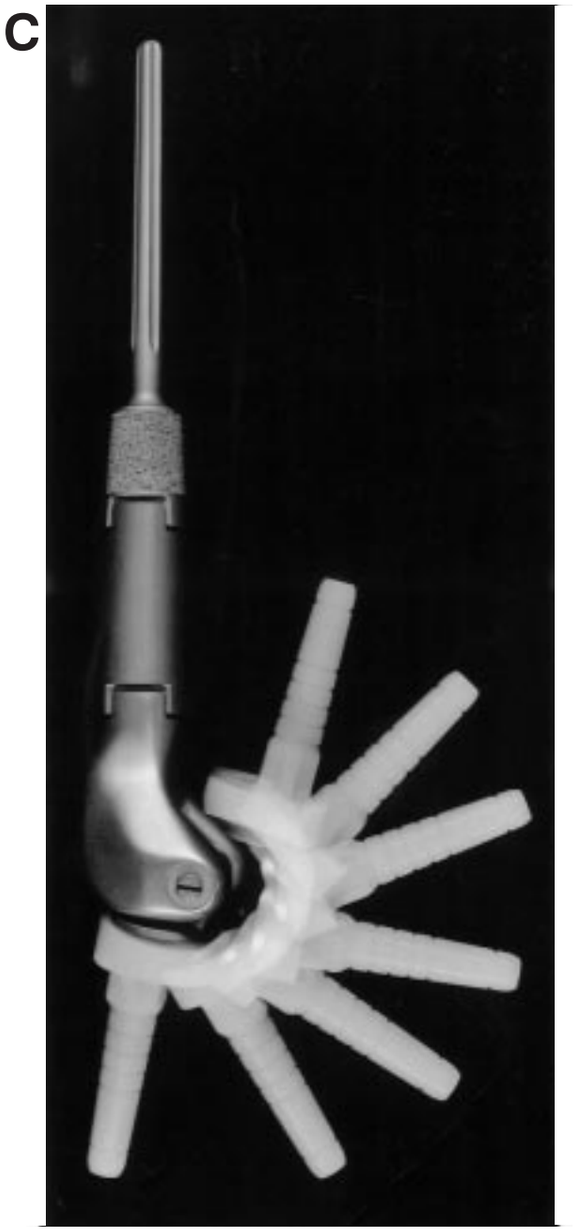


Figure 25.5 C,D

rotation, and increases the degree of freedom for the joint. The saddle component connects to a series of interchangeable modular bodies that, in turn, connect to a standard cemented hip component. This device preserves limb length following resection of the periacetabulum (type 2 pelvic resection, modified internal hemipelvectomy) while functioning like a total hip prosthesis. The clinical and functional results following saddle reconstruction of the pelvis with this system have been extremely good.[6]

CURRENT DESIGNS – THE MODULAR REPLACEMENT SYSTEM (MRS)

A second-generation universal system, originally called the modular segmental replacement system (MSRS) and recently renamed the modular replacement system (MRS), was introduced in 1988 (Howmedica Inc., Rutherford, NJ). This system was designed to provide modular replacements for the proximal humerus, proximal femur, total femur, distal femur, and proximal

tibia. Careful failure analysis of custom endoprostheses guided the design of the new modular system. Significant design features are the following:

1. *Cemented stems*. The use of bone cement (methylmethacrylate) has a substantial track record in joint replacement. Long-term outcome studies now cover nearly 25 years. Cement is well tolerated biologically and functions as a grout that compensates for any mismatch between the geometry of the medullary canal and the prosthetic stem. Additionally, aseptic loosening, which was once believed to be associated with the bone cement and even termed "cement disease", has now been attributed to the biologic response to wear debris, particularly polyethylene. Cemented stems ensure immediate fixation, avoid the need for postoperative bracing or prolonged non-weight-bearing, and permit early rehabilitation.
2. *Multiple stem diameters*. Experience with custom endoprostheses demonstrated a substantial risk of stem fracture secondary to fatigue failure when small-diameter stems were used. The modular system permits the use of the largest stem diameter possible for a given patient, thereby minimizing this risk. In addition, the use of a facing reamer that matches the outer radius of the stem/body junction allows for a perfect seat for the prosthesis, and protects the stem from bending stresses.
3. *Circumferential porous coating*. A porous surface composed of two layers of sintered beads around the body of the prosthesis was originally designed to permit the ingrowth of bone graft placed at the bone/prosthesis junction (extraskeletal fixation) (Figure 25.6). This bone graft can protect the prosthetic stem by sharing all bending and loading stresses on the implant. A potentially more significant benefit of this feature is that it supports the ingrowth of soft tissue, which produces a seal between the debris-laden articular and periprosthetic fluid and the vulnerable bone–cement–stem interface. Termed the "biologic noose", this seal has been shown by Ward *et al*.[7] to essentially eliminate the risk of osteolysis when used in endoprosthetic reconstructions.[8]
4. *Rotating hinge knee* (Figure 25.5C). The Kinematic rotating hinge knee, originally designed as a semi-constrained total knee replacement, was adopted for this system because it not only provides stability but also offers a high degree of freedom of motion. This is critical for reconstructing the knee when all of the cruciates and collateral ligaments have been resected or are otherwise incompetent.

Other important new features of this system include full instrumentation to assist in preparing the canal for implantation, and a series of assembly modules that hold and impact the modular components together. Metal loops and porous coated surfaces exist at the important insertion points of significant functional tendons (e.g. extensor mechanism for a proximal tibial replacement) to permit dependable soft-tissue reattachment and fibrous ingrowth into the prosthesis.

BIOMECHANICAL CONSIDERATIONS FOR ENDOPROSTHETIC RECONSTRUCTION

Prosthetic Design

Careful observation of modes of failure over time is critical to understanding the mechanical and material limitations of any manufactured device. Reports of long-term clinical experience with various custom endoprosthetic systems served as a basis for many of the design features of the current MRS. The process of observation and redesign should not, however, be viewed as a one-off activity. Continued analysis of the results of each modification to the system is required to ensure that corrections of existing problems do not in themselves lead to unforeseen new difficulties.

For the early devices a major mode of catastrophic mechanical failure was fracture of the intramedullary stem. This problem was caused by a number of unrelated factors. Errors in the mixture of the alloys used in the manufacturing process, as well as in processes used in creating the device (e.g. casting, forging, machining, tempering) can leave microscopic structural defects within the stem that can be susceptible to fatigue failure over time. The biomechanical loads carried by an endoprosthesis can be staggering. Experiments with instrumented hip replacements have documented a joint reaction force of 2.3–3.3 times body weight during routine weight-bearing and 0.86–2.19 times body weight during single-leg stance.[8] Much greater loads occur with impact activities. An average person has a stride length of around 0.6 m when walking at a normal pace[9] of 1.2 m/s. This translates to two steps (heel strike to heel strike) every second. If one assumes that an average of 15 min of every waking hour are spent walking, this equates to over 10 million cycles of loading each year. What is impressive is not that some stems fail over time but that many stems survive.

The most important determinant of the strength of a stem is its cross-sectional diameter. Resistance to bending in a given plane is proportional to the radius in that plane raised to the fourth power. Consequently, small increases in the diameter of the stem lead to significant gains in rigidity and resistance to bending. This is supported by the fact that the stems that typically fracture in custom implants are typically very small (≤ 9 mm in diameter).[10] The MRS system enables

the surgeon to implant the largest-diameter stem that can fit within the intramedullary canal. This factor alone can dramatically reduce the risk of stem failure.

Modular systems, however, require a dependable method of assembly. The Morse taper, and its many proprietary modifications, enables the surgeon to assemble a prosthesis simply by the impacting of its components (Figure 25.6A). Long-term results of modular hip replacements have made orthopedic surgeons familiar with this method of fixation. While isolated examples of component dissociation have been reported for various modular implants of all designs, our experience with over 100 MRS implants has failed to reveal any problems with this taper. A crucial step in the assembly is to ensure that the taper is completely dry and free of debris that may interfere with complete

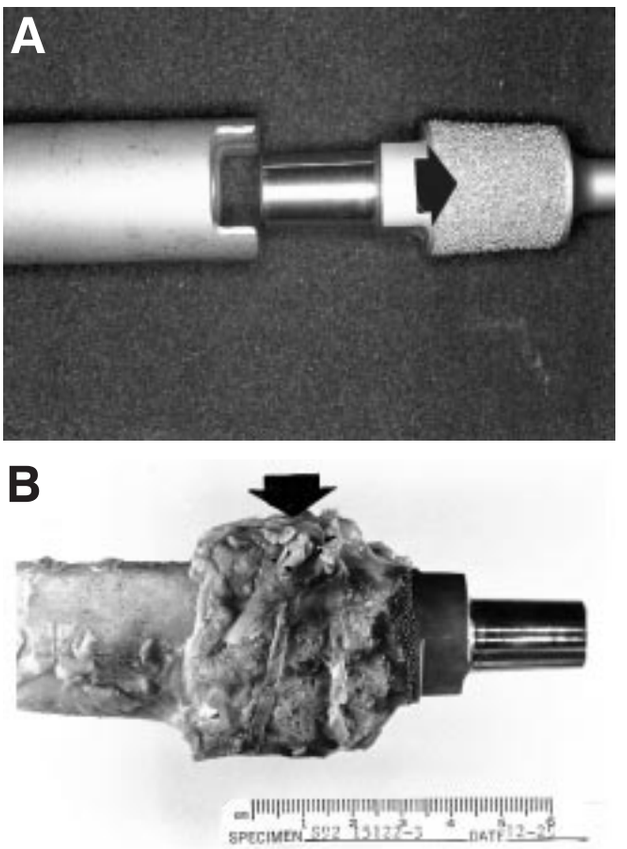


Figure 25.6 Extracortical fixation of a distal femoral prosthesis. (**A**) Close-up of the taper of the Modular Replacement System (Howmedica, Inc., Rutherford NJ). Note the porous coating of the body of the stem (arrow). (**B**) Autopsy retrieval of distal femoral prosthesis. The bone graft (arrow) is well fixed to the porous coating. Note the beads are hardly visible. The Dacron (3 mm) tape is intact and is utilized to fix the autogenous bone graft to the porous-coated segment of the prosthesis. Note there is no evidence of corrosion of the taper. This prosthesis was in for 5 years. (**C**) Typical radiographic view of extracortical bone fixation (arrow) from the host bone to the porous-coated segment of a custom prosthesis. This is approximately 4 years since implantation. Extracortical bone fixation was first developed as a practical concept following the introduction of porous coating by Howmedica (Rutherford , NJ) during the early 1980s.

seating of the taper. Failure to do this can result in a loose fit. The ability to create a loose fit has actually been used to advantage clinically in patients requiring a temporary prosthesis (such as a spacer for treating an infection) that can be easily disassembled to permit revision surgery.

A second method of protecting a stem from failure takes advantage of the biologic properties of bone. A bone bridge, termed "extracortical bone fixation", is created between the outer diameter of the prosthetic body and the outer bone cortex, bypassing the relatively vulnerable transition zone between the prosthetic body, prosthetic stem, cement, and diaphyseal bone (Figure 25.6).[11] The bone bridge protects the stem by increasing the diameter of the composite mechanical structure that resists bending moment, thereby reducing the overall stress applied to the actual stem. This method of biologic fixation, however, requires that the bone graft adheres or attaches to the prosthesis. Early attempts at simple onlay bone graft were disappointing because the graft was often resorbed. Fixation of the onlay graft with a circumferential Dacron tape, however, has been shown to provide enough compression so that the bone graft not only adheres to but also hypertrophies around the prosthesis. This outcome was the original impetus for placing porous-coated surfaces on the prosthetic body adjacent to the stem. Clinical experience has shown that this effect is readily reproducible. Additional application of demineralized bone matrix containing bone morphogenic protein (BMP) is a promising method of further improving this method of fixation.

A nonbiologic method of protecting the stem is an external flange, which is utilized in the European modular system. Biomechanically, the flange increases the diameter of the composite mechanical structure. Unfortunately, the clinical results of flanges have been disappointing. Significant stress shielding and resulting bone loss of the cortex located between the stem and the external flange occur. This destabilizes the interface between the stem and the bone, resulting in increased micromotion that produces rapid fatigue failure of the transfixation screws placed through the flange into cortical bone. The wear debris associated with the failed screws, combined with prosthetic micromotion, results in a spiral of increasing loosening. Eventually, the stem fixation fails. Despite extensive modification of the flange positioning and the number of transfixation screws, this design remains inferior to the MRS produced in the United States.

An unexpected benefit of extracortical bone fixation has been the clinical observation that osteolysis surrounding the cemented stem does not appear in regions immediately adjacent to the porous coating on the body. This effect, termed the "biologic pursestring", is believed to occur because tissue that has adhered to the porous coating isolates the stem–cement–bone complex from the wear-debris-laden fluid that surrounds the joint and prosthetic body. In addition to supporting laboratory and clinical data implicating polyethylene wear-debris in the genesis of osteolysis, this observation indicates that a circumferential porous coating is a necessary feature for any prosthetic bone implant. Accordingly, the MRS features circumferential beads, that permit bone grafting for extracortical fixation and stress reduction of the cemented stem, as well as ingrowth of fibrous tissue to prevent osteolysis and loosening of the cemented stem.

Selection of an appropriate joint mechanism is critical both to the functional outcome and the long-term durability of an endoprosthesis. A prosthetic joint must provide stability, particularly in situations with significant resection of soft-tissue constraints (ligaments, capsules). Reconstruction of the hip joint is readily accomplished by means of a bipolar hemiarthroplasty, given the inherent stability of a ball-and-socket joint. Dislocation can be prevented through meticulous reconstruction and/or augmentation of the hip capsule. Because the majority of these patients are young, there are few indications for total hip replacement. Tumors requiring resection of the acetabulum may be reconstructed with a saddle endoprosthesis.

Replacement of the knee is more difficult, largely because of the unique anatomical and biomechanical features of this joint. Early prosthetic designs consisted of a simple hinge mechanism (Walldius, Guepar) or a constrained ball-and-socket design (Spherocentric). However, highly constrained systems such as the early total knee designs, have a high incidence of failure related to loosening or breakage. The most probable reason is that normal knee biomechanics include gliding translations and rotations that cannot be duplicated by a simple hinge (Figure 25.5). The original HMRS prosthesis used a simple hinge joint supported by polyethylene bushings. The high incidence of bushing failure noted in clinical series supports this assumption. Accordingly, the current MRS relies upon the Kinematic rotating hinge design. This semiconstrained mechanism permits three major degrees of freedom (superior/inferior translation, internal/ external rotation, and flexion/extension), one minor degree of freedom (five degrees of varus/valgus rotation or tilt), and constraints on medial/lateral and anterior/ posterior translation. This mechanism reproduces the restraints provided by the cruciate and collateral ligaments, and creates a very stable knee, even when these primary restraints of the knee have been totally resected. Preservation of the four degrees of freedom

helps protect the polyethylene bushings that support the primary axle and reduce torques transmitted to the prosthetic/bone junctions.

FUNCTIONAL RECONSTRUCTION AND ANATOMIC CONSIDERATIONS

The functional outcome of an endoprosthetic replacement is directly related to the amount of functional muscle preserved at the time of surgical resection. This simple observation can be used to project an outcome for an individual patient prior to surgery. For example, a large high-grade sarcoma of the proximal humerus requires an extra-articular resection of the shoulder, sacrificing the entire rotator cuff, in conjunction with sacrifice of the axillary nerve to achieve a true oncologic wide resection. Given the magnitude of this resection the optimal outcome is a stable painless shoulder that permits functional use of the elbow, forearm, wrist, and hand. This is accomplished by combining a static suspension of the prosthesis from the remaining scapula and clavicle, with a dynamic suspension composed of local muscle transfers that stabilize the shoulder and facilitate internal rotation (i.e. transfer of the pectoralis major). In contrast, the resection of rare low-grade sarcoma or a palliative resection for metastatic disease can be safely accomplished by performing a marginal resection, preserving many of the critical functional elements around the shoulder. Shoulder function will be much greater if the means of powering the shoulder are preserved.

These same principles hold true for endoprosthetic replacement of any portion of the skeleton, and are independent of the design of the prosthesis. However, prosthetic design can help facilitate the overall outcome in several key aspects. First, exact duplication of the skeletal anatomy being reconstructed is not necessary to achieve an excellent outcome. On the contrary, it is preferable to minimize prosthetic protuberances (such as a faux greater trochanter for a proximal femoral replacement) so that a better closure can be achieved with the remaining soft tissues following resection. Minimization of the medial/lateral diameter of the components around the knee can also greatly facilitate soft tissue closure of the knee mechanism. Second, functional groups have traditionally been reattached by making drill holes to pass sutures through the prosthesis. The loops allow the surgeon to pass sutures if desired, but also permit a tendon to be passed though the loop so that it may be sewn directly to itself. The positioning of these loops is therefore a critical design feature. Again, exact mimicry of the skeletal anatomy fails to account for tissue loss during the resection process; this must be considered in the placement of the attachment sites. The soft-tissue attachment may be further reinforced by adding bone graft to the site, where a porous coating can permit ingrowth of tissue. Other methods of soft-tissue attachment, such as spiked screw plates designed to firmly hold a tendon, are under investigation.

The use of a polished smooth stem inserted with bone cement using "third-generation" cement techniques (i.e. vacuum mixing to reduce porosity, pressure injection into a prepared canal with an inserted cement restrictor, and centralization of the stem during the insertion process), remains the gold standard for fixation of an endoprosthesis. This is particularly true in patients undergoing adjuvant treatments such as systemic chemotherapy or radiation that can inhibit bone growth. The major advantage of cementation for oncologic patients is that it produces the immediate rigid and painless fixation, which reduces the need for postoperative protected weight-bearing or bracing and permits early functional rehabilitation. This has a tremendous positive physical and mental impact on the patient. Cement also conforms to the biologic and stem geometry, maximizing the contact between the stem and bone. In addition, the injection of cement can strengthen and compensate for the reduced mechanical properties of bone, which may be significantly weakened. Osteoporosis from disuse and osteopenia from poor nutritional intake, increased metabolic wasting, and an altered hormonal milieu, frequently occur in patients with chronic disease as well as in those receiving chemotherapy. Certain patients may, however, be candidates for "biologic fixation", such as a porous-coated press-fit stem.[11] For example, a young, active patient with excellent bone stock undergoing revision surgery or resection of a low-grade tumor for which adjuvant treatment is not indicated may benefit from the long-term fixation that a press-fit stem may offer. One advantage of a system such as the MRS is that a simple, customized stem that matches a patient's unique anatomy may be readily manufactured and used in conjunction with the other modular parts of the system.

STAGES OF LIMB-SPARING SURGERY

The three stages of a limb-sparing procedure are as follows:

1. tumor resection;
2. skeletal reconstruction; and
3. soft-tissue coverage and muscle transfers to restore function.

The majority of this textbook deals with the surgical techniques required to perform a safe oncologic resection of a primary bone sarcoma. Successful functional

reconstruction of the resulting defect consists of two separate but dependent stages. The first is the implantation of an endoprosthesis, which restores the length and stability of the skeleton. The second is the soft-tissue reconstruction that is required to cover the prosthesis and restore function to the joint.

The endoprosthesis is implanted in a systematic fashion. By rigorously following the same steps the surgeon can achieve a reliable, long-lasting reconstruction. Meticulous attention to soft-tissue reconstruction is vital to reducing the incidence of wound breakdown and secondary prosthetic infection.

GUIDELINES FOR SKELETAL RECONSTRUCTION (STAGE 2)

Endoprosthetic Selection and Implantation

Following resection of a segment of bone, the specimen is carefully measured in order to select the best-fitting prosthetic components. Trial components are provided to enable a rapid comparison with the specimen, as well as to perform trial reductions prior to selection and assembly of the final prosthesis. The following steps are necessary to prepare the intramedullary canal for stem insertion. Note that the selection of the stem diameter is dependent upon the anatomy of the canal, which is sequentially reamed in order to accommodate the largest-diameter stem possible.

1. Frozen section evaluation of the marrow contents by a skilled musculoskeletal pathologist is required to ensure that no tumor cells are present within the bone marrow prior to the preparation of the intramedullary canal. After insertion of a guidewire the canal is sized and enlarged with a flexible intramedullary reamer.
2. After the stem diameter has been selected, a facing reamer is inserted into the canal to machine a curved radius in the free end of the bone. This radius is designed to match the radius of curvature at the stem/body junction of the prosthesis, and thereby maximizes the fit between the prosthetic body and the bone.
3. The reamed canal is cleaned. A pulsatile lavage and an intramedullary brush helps remove clots and bone debris. A plastic cement restrictor is inserted to assist in pressurization of the cement at the time of implantation. The canal is packed to minimize bleeding during the remaining preparatory steps.
4. The adjacent joint surface is then prepared to accept the prosthesis. The steps required vary by anatomic site and are outlined in the following section.
5. A trial prosthesis is assembled and inserted. The surgeon checks for implant position, joint stability, limb length, and range of motion. Length discrepancies are corrected by removing additional bone using the facing reamer (for small adjustments), varying the size of the polyethylene component in the proximal tibia (for distal femoral replacements), or changing the body segment selected.
6. The final prosthesis is assembled on a back table using the assembly holders and impactors provided with the system. All Morse tapers must be completely clean and dry to ensure a mechanically sound interference fit.
7. Cementation of the canal and insertion of the assembled endoprosthesis is performed using third-generation techniques.
8. The final step prior to the soft-tissue reconstruction is the application of onlay bone graft for extracortical fixation. Autogenous bone graft (often taken from the adjacent joint surface) is positioned across the prosthetic bone junction and tied in place using a large-diameter dacron tape.

Preparation of the Adjacent Joint by Anatomic Site

The adjacent joint surface must be prepared to accept the endoprosthesis prior to assembly of the final component. The preparation process varies with the anatomic location, as described below.

Shoulder (Proximal Humerus)

The majority of patients treated for tumors of the proximal humerus undergo an extra-articular resection of the shoulder in order to ensure an adequate surgical margin.[12] A combination of static and dynamic restraints around a unipolar prosthetic head provides stability for the joint. Selection of the head diameter is based on the local anatomy. Large-diameter Dacron tapes are used to suspend the prosthesis from the remaining scapula and/or clavicle (static restraint). Multiple muscle transfers, including the pectoralis major muscle, are performed to achieve prosthetic coverage and joint stability.

Proximal Femur (and Total Femur) (Figure 25.7)

Bipolar hemiarthoplasty is the preferred method of reconstruction for the hip. Resection of the surrounding tissue of the acetabulum significantly denervates the acetabulum, and creates a painless hip, even in young, very active, patients. Conversion to a total hip is possible, but rarely indicated. The bipolar head size is chosen after measurement of the acetabulum (either with sized acetabular trials by direct measurement of

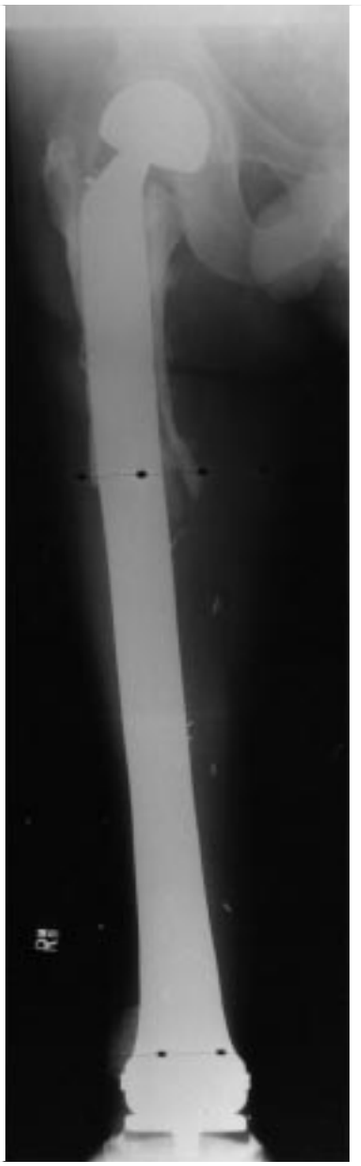


Figure 25.7 Radiograph of a large total femoral custom prosthesis with a bipolar hip component and a Kinematic rotating hinge prior to the use of the modular design (1988).

the diameter or of the excised femoral head). Following implantation of the prosthesis, joint stability is enhanced by transfer and myotenodesis of the psoas and the external rotators. Dacron tapes are placed around the prosthetic neck, where they act as static restraints. This method virtually eliminates the risk of dislocation in the postoperative period.

Distal Femur (and Total Femur) (Figure 25.8)

The top 1 cm of the tibial plateau is removed with an oscillating saw (a neutral cut without posterior slope) and saved for the extracortical onlay bone graft. Trial components are used to select the largest tibial component that fits on the proximal tibia with minimal medial–lateral overlap. (Overlap must be avoided to facilitate the soft-tissue closure over the prosthesis.) The tibial canal is prepared with a guide placed over the plateau to create a distal bone plug and proximal box to accommodate the stemmed polyethylene tibial-bearing component. Following trial reduction of the selected components the tibial insert is cemented into place using third-generation cement techniques.

Proximal Tibia (Figure 25.9)

The femoral condyles are resurfaced using a technique similar to that used for a total knee replacement. The femoral canal is opened with a reamer to allow for insertion of an intramedullary guide. A distal femoral cut is performed to remove 8 mm of the condyles. Anterior and posterior chamfers are created with an oscillating saw or a high-speed burr to accommodate the standard-sized femoral component. After trial reduction this component is cemented into place using third-generation cement techniques.

GUIDELINES FOR SOFT-TISSUE RECONSTRUCTION (STAGE 3)

The basic goals of the soft-tissue reconstruction are to provide adequate coverage of the prosthesis and restore muscle power and joint stability. A variety of local and regional muscular rotation flaps must be performed to maximize functional outcome and ensure adequate coverage of the prosthesis. Meticulous attention to handling the soft tissues and preserving the regional blood supply is essential at this step. Complete muscular coverage of the prosthesis minimizes the risk of periprosthetic infection related to superficial wound breakdown (marginal necrosis) that occasionally occurs following the creation of large flaps during an oncologic resection. Muscle transfers also improve stability of the reconstructed joint, and restore useful joint function. Aggressive mobilization of the remaining muscles crossing a given joint, as well as specific muscular rotational flaps, permits the surgeon to achieve all of these goals without creating free flaps.

To provide functional power to the limb, soft tissue must be attached to the prosthesis. This entails attaching the major tendons to the prosthesis (using the provided metal loops) and creating a musculotendinous cuff around the body of the prosthesis. In addition,

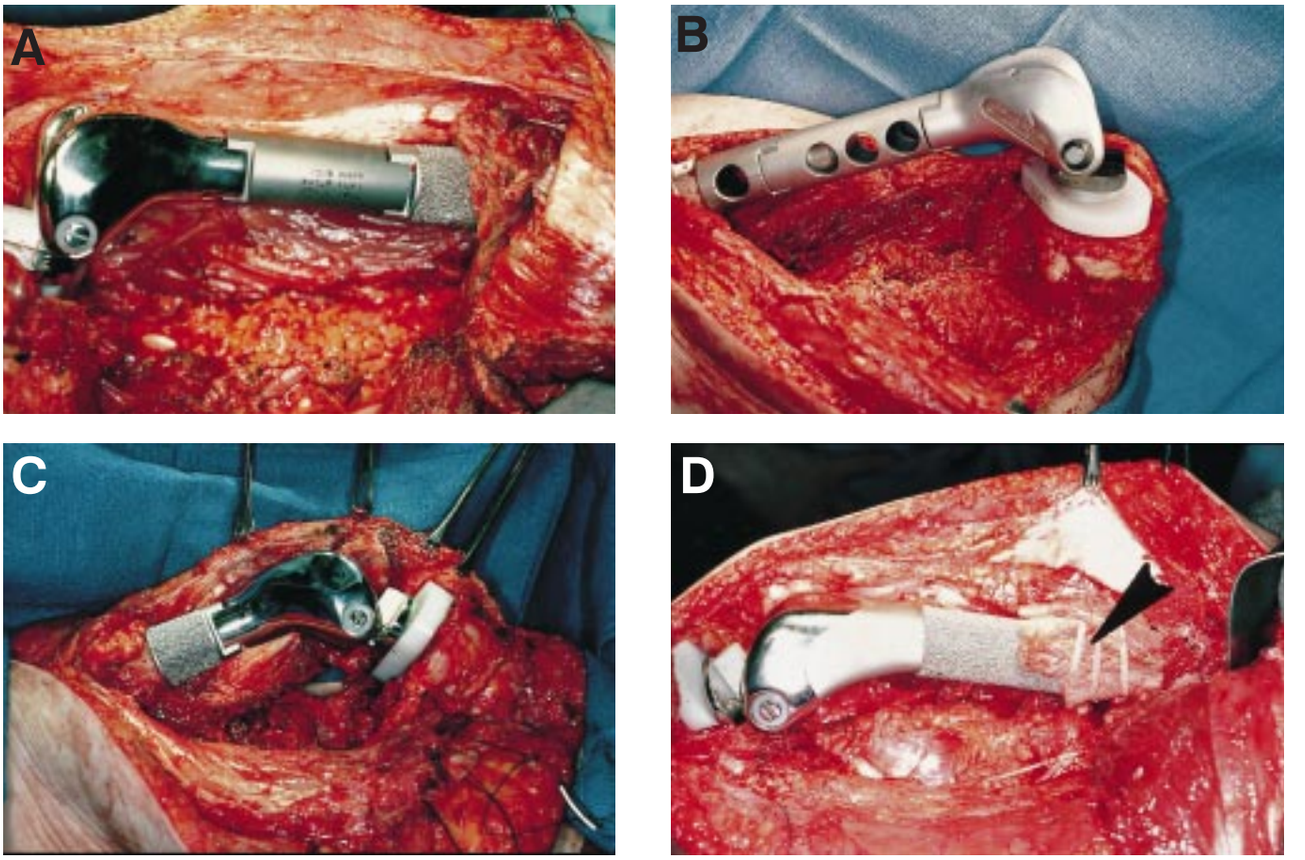


Figure 25.8 Intraoperative photographs of a distal femoral replacement. (**A**) A completely assembled distal femoral prosthesis (Modular Replacement System, Stryker Howmedica Osteonics, Inc., Allendale, NJ). (**B**) Trial prosthesis to determine the appropriate length and tension. Note a trial prosthesis of the Modular Replacement System has large holes in the body and stem to avoid mistaken implantation. (**C**) Distal femoral replacement without the use of a body. This is utilized for small segmental resections and is required for some Stage III giant cell tumors and small (Stage I) intra-osseous sarcomas. (**D**) Intraoperative photograph of a custom prosthesis used prior to 1988 with a large area of the body being porous coated. Note the attached bone graft to the porous coating with Dacron tape (arrow) is to permit extracortical fixation. New bone formation is usually visualized radiographically between 8 and 16 weeks postoperatively.

restoration of proper limb length helps ensure stability of the reconstruction. As noted previously, the prosthesis has a beaded porous coating at sites of important tissue attachments. The porosity allows both for bone and fibrous ingrowth: a new tendon–bone junction is created by adding bone graft between the porous surface of the prosthesis and the tendon which is held firm to the prosthesis with Dacron sutures.

Details of common muscle transfers are provided elsewhere in this textbook. These routine muscle transfers include the following:

1. Shoulder: transfer of the pectoralis major and latissimus dorsi muscles covers and dynamically stabilizes a proximal humeral prosthesis. Dacron tapes are used to statically suspend the prosthesis from the scapula.
2. Hip: the psoas and external rotators are transferred to create a pseudocapsule around the prosthetic head. This capsule is reinforced with circumferential Dacron tapes to prevent dislocation. Reattachment of the abductor muscles is necessary to minimize the Trendelenberg lurch in the postoperative phase. This limp improves over time with strengthening of the abductors.
3. Knee: 25% of distal femoral replacements and all proximal tibial replacements require rotation of a gastrocnemius muscle (typically the medial head) to

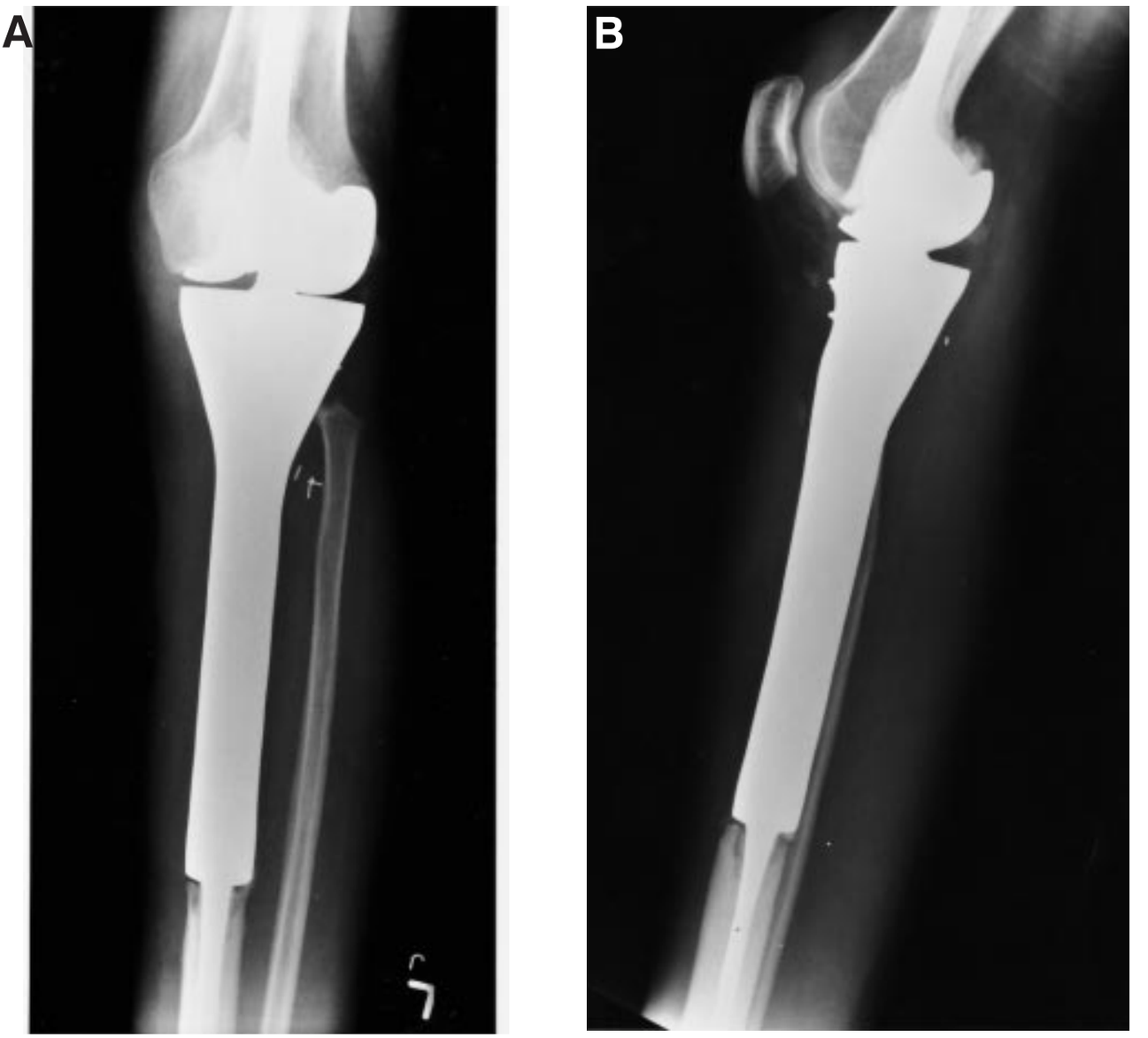


Figure 25.9 Custom segmental prosthesis with a spherocentric knee component utilized prior to the early 1980s for the proximal tibia. (**A**) The anterior–posterior view. (**B**) Lateral view. Note that this is a spherocentric knee design and not a rotating hinge. This was the original design utilized for knee replacements during the 1970s. A rotating hinge knee became available during the early 1980s.

repair the soft-tissue defect following resection of a tumor around the knee. This local flap is incorporated into the reconstruction of the patellar tendon in patients undergoing proximal tibial replacements.[13]

Final closure of the wound may be jeopardized by skin loss following resection of a biopsy tract. Patients with very large tumors generally have extra skin because the growing tumor acts as an internal skin stretcher. This extra skin can be rotated to facilitate the wound closure. Excess skin along the incision should be excised to avoid marginal wound necrosis related to regional devascularization during the creation of large flaps. To avoid pressure-induced ischemia, patients with tight skin closures are best served by leaving the skin open and performing a primary or secondary split-thickness skin graft. Patients must be maximally elevated in the postoperative phase to reduce swelling that can

jeopardize the wound closure. Use of large-bore closed suction drains and correction of any postoperative coagulopathies is necessary to prevent hematomas. Patients who develop hematomas or wound breakdown require aggressive treatment in the operating room to prevent secondary infection of the endoprosthesis.

CLINICAL RESULTS FOLLOWING ENDOPROSTHETIC REPLACEMENT

Prosthetic survival has improved dramatically since the development of advanced surgical techniques, better prosthetic designs, and modern manufacturing techniques. Results of some early custom prostheses were disappointing, leading many surgeons to use allografts or other methods of reconstruction. More recently, as high rates of allograft complications have been reported, there has been increasing interest in the new generation of endoprostheses.

Complications are not uncommon with any type of limb-sparing procedure. The majority of these patients have altered immune systems from chronic disease, chemotherapy, and malnutrition. Many patients are anemic and have clotting abnormalities, including thrombocytopenia. Long-term indwelling catheters, used for the administration of chemotherapy, may cause a high incidence of line infections, that can jeopardize an endoprosthetic replacement through hematogenous spread of bacteria. The local anatomic location of a tumor may disrupt the venous and lymphatic drainage of the extremity during resection, leading to venous stasis, swelling, and lymphedema. This can quickly result in flap necrosis during the postoperative period. Secondary infection and eventual amputation may be the result. Finally, oncologic complications, including local recurrence of tumor or tissue necrosis from radiation, may result in failure of a limb-sparing procedure.

Complications specific to endoprosthetic reconstruction may be related to mechanical or biologic factors. Prosthetic fracture, dissociation of modular components, fatigue failure, and polyethylene wear may be encountered. Improved designs and metallurgy can significantly reduce the incidence of these problems (Figure 25.10). Our experience with more than 150 MRS implants over the past 12 years has revealed no stem fractures, body fractures, or taper dissociation. Polyethylene wear does occur, but less than 5% of patients with bushings in the rotating hinge mechanism have required exchange of these components.

Nonmechanical (biologic), failure of an endoprosthsis may occur as a result of aseptic loosening, or fracture of bone around the prosthesis. Joint stability is no longer a problem. Moreover, the use of circumferential porous coating has dramatically reduced the incidence of aseptic loosening in our patients. Surgical technique, as well as the use of cemented stems, has prevented periprosthetic fractures during surgery. The few patients who have developed fractures as a result of blunt trauma (falls, auto accidents) have been treated successfully with casting and protected weight-bearing.

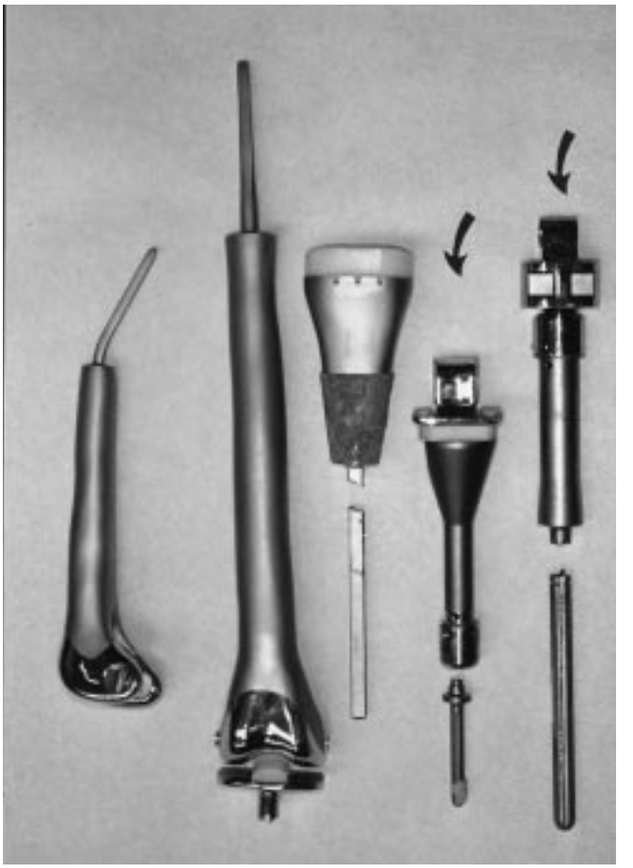


Figure 25.10 Composite photograph showing failures of several different prosthetic devices utilized during the 1980s and the various modes of failure. The most common mode of failure was either stem breakage or bending. Today, stems are heavily forged, have a curved transition at the junction with the prosthesis and are rarely less than 9 mm in diameter.

ENDOPROSTHETIC SURVIVAL

The majority of published United States series looking at the survival of endoprosthetic reconstructions are based on small series of custom components implanted in the late 1970s and early 1980s. These include the following:

1. Chicago: 66% 10-year survival for distal femoral replacements (DFRs).[14]
2. England: 64% 7-year survival rate for DFRs.[15]
3. New York: 89% proximal femur, 59% distal femur, 54% proximal tibia.[16]
4. Washington: 83% 5-year and 67% 10-year survival for tumors at all sites.[17]

A more modern series was based upon experience with the HMRS system in Europe. Long-term data for the distal femoral replacement have been disappointing; an overall complication rate of 55%, a mechanical failure rate of 6% for stem breakage, and 42% polyethylene failure after a follow-up of 64 months[18]. As a result this particular system was never approved for use in the United States.

Our experience with the current-generation MRS has been very gratifying. Since its introduction in the 1980s, over 150 implants have been used at our center. Results of the first 100 prostheses, which have been followed for a minimum of 2 years, are summarized in Table 25.1.

For this series, "failure" was defined as removal of the prosthesis for any reason. Most notably there have been no mechanical failures to date involving the stems, bodies or tapers. All the prostheses that failed were the result of periprosthetic infection, at a 7% rate. Although this is significantly higher than the infection rate associated with total joint replacement, the majority of these patients were immunocompromised as the result of chemotherapy treatments. The rate of polyethylene bushing failure has been approximately 5%.

Table 25.1 Results of the first 100 MRS

Site of prosthesis (no.)	*Survival at median follow-up*	*Kaplan–Meier Survival at 10 years*
Distal femur (48)	90.7% at 63.0 months	90%
Proximal humerus (22)	98% at 77.7 months	98%
Proximal femur (15)	100% at 58.8 months	100%
Proximal tibia (13)	78% at 61.7 months	78%
Total femur (2)	100% at 25.4 months	
All sites (100)	*88.2% at 64.4 months*	*88%*

FUTURE DIRECTIONS FOR ENDOPROSTHETIC RECONSTRUCTION

The current MRS prosthesis has greatly facilitated limb-sparing surgery following resection of bone sarcomas. Its success has expanded the indications for endoprosthetic reconstruction to include bone defects for nononcologic problems. Increasing experience with this system for salvage of failed total joint replacements, chronic nonunions of fractures, and reconstruction following radical resection of osteomyelitis has shown that the proven concepts of limb- sparing surgery can be easily applied to many other clinical situations.

Current research to improve the performance of the MRS prosthesis is focusing on improved work on advanced bioactive coatings, alternative methods of stem fixation, and improved methods of attaching soft tissue. Continued work on improved metallurgy and polymers, particularly with the introduction of cross-linked polyethylene, is expected to improve the durability of the MRS. Although future advances in tissue engineering hold the promise of artificially engineered bones, we expect that endoprosthetic reconstruction will remain the implant of choice of orthopedists for many years to come.

References

1. Enneking WF. Clinical Musculoskeletal Pathology. Gainsville: University Press of Florida; 1977.
2. Gebhardt MC, Flugstad DI, Springfield DS, Mankin HJ. The use of bone allografts for limb salvage in high-grade extremity sarcomas. Clin Orthop. 1991;270: 181–96.
3. Hejna MJ, Gitelis S. Allograft prosthetic composite reconstruction for bone tumors. Sem Surg Oncol. 1997;13: 18–24.
4. Marcove RC, Lewis MM, Rosen G *et al*. Total femur and total knee replacement. A preliminary report. Clin Orthop. 1977;126:147–52.
5. Capanna R, Morris HG, Campanacci D *et al.* Modular uncemented prosthetic reconstruction after resection of tumours of the distal femur. J Bone Joint Surg. 1994;76B: 178–86.
6. Aboulafia AJ, Buch R, Mathews J, Li W, Malawer MM. Reconstruction using the saddle prosthesis following excision of primary and metastatic periacetabular tumors. Clin Orthop. 1995;314:203–13.
7. Ward WG, Johnson KS, Dorey FJ, Eckardt JJ. Extramedullary porous coating to prevent diaphyseal osteolysis and radiolucent lines around proximal tibial replacements. J Bone Joint Surg. 1993;75A:976–87.

8. An K, Chao EYS, Kaufman KR. Analysis of muscle and joint loads. In: Mow VC, Hayes WC, editors. Basic Orthopaedic Biomechanics, 2nd edn. New York: Lippincott Raven; 1997:000–00
9. Andriacchi TP, Natarajan RN, Hurwitz DE. Musculoskeletal dynamics, locomotion and clinical applications. In: Mow VC, Hayes WC, editors. Basic Orthopaedic Biomechanics, 2nd edn. New York: Lippincott Raven; 1997:000–00.
10. Henshaw RM, Malawer MM. Survival of modular versus custom endoprostheses for limb salvage: are we actually doing better? Presented at American Academy of Orthopaedic Surgeons 1998 Annual Meeting – Scientific Program; Paper No. 157, 20 March, 1998.
11. Malawer MM, Canfield D, Meller I. Porous-coated segmental prosthesis for large tumor defects. A prosthesis based upon immediate fixation (PMMA) and extracortical bone fixation. In: Yamamuro T, editor. New Developments for Limb Salvage in Musculoskeletal Tumors. New York: Springer; 1989:247–55.
12. Malawer MM. Tumors of the shoulder girdle. Technique of resection and description of a surgical classification. Orthop Clin N Am. 1991;22:7–35.
13. Malawer MM, Price WM. Gastrocnemius transposition flap in conjunction with limb-sparing surgery for primary bone sarcomas around the knee. Plast Reconstr Surg. 1984;73:741.
14. Rougraff BT, Simon MA, Kneisl JS, Greenberg DB, Mankin HJ. Limb salvage compared with amputation for osteosarcoma of the distal end of the femur: a long-term oncological, functional, and quality of life study. J Bone Joint Surg. 1994;76:649.
15. Roberts P, Chan D, Gimer RJ, Sneath RS, Scales JT. Prosthetic replacement of the distal femur for primary bone tumours. J Bone Joint Surg. 1991;73B:762.
16. Horowitz S, Glasser D, Lane J, Healey J. Prosthetic and extremity survivorship in limb salvage: how long do the reconstructions last? Clin Orthop. 1993;293:280.
17. Malawer MM, Chou LB. Prosthetic survival and clinical results with use of large-segment replacements in the treatment of high-grade bone sarcomas. J Bone Joint Surg. 1995;77A:1154–65.
18. Capanna R, Morris HG, Campanacci D *et al*. Modular uncemented prosthetic reconstruction after resection of tumours of the distal femur. J Bone Joint Surg. 1994;76B: 178–86.
19. Henshaw RM, Jones V, Malawer MM. Endoprosthetic reconstruction with the modular replacement system. Survival analysis of the first 100 implants with a minimum 2 year follow-up. Proceedings, Fourth Annual Combined Meeting of the American and European Musculoskeletal Tumor Societies, Washington, DC; 1998:90.