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REVIEW ARTICLE

Expandable tumor prostheses in children

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Summary

Any surgical resection in the lower extremities in children will cause a leg length discrepancy from physeal resection. To avoid the resulting functional deficit, leg length discrepancy must be reconciled with surgical techniques to approximate equal leg lengths at skeletal maturity. Currently there are several manufacturers who offer options for prosthetic reconstruction with expandable implants. These implants can be expanded to a length projected on the basis of three factors: the length of bone resected, the anticipated future growth of the contralateral extremity, and the estimated discrepancy of limb length at skeletal maturity.

In this article, we review the basic principles and guidelines for prediction of remaining bone growth and planning lengthening in children, and present the currently available expandable prostheses and the evolution performed over time.

Key words: bone growth, bone tumors, children, expandable prostheses

Introduction

Primary bone tumors are often encountered in children. These tumors are frequently found close to the physes of long bones, the most common locations being the distal femur and the proximal tibia [1,2]. Current advances in imaging and adjuvant treatments have led to improved survival and local control, which has made limb salvage feasible without compromising survival. However, in this age group, any surgical resection will cause a leg length discrepancy from physeal resection [3,4]. The resulting functional deficit, if untreated, will lead to significant gait disturbances and low back pain, in addition to severe cosmetic effects on the shortened leg, especially in school years when the child may require orthotics and other aids for ambulation [4].

Complete tumor resection, equal limb length at maturity and good functional outcome are the main goals of tumor surgery in children. Leg length discrepancy must be reconciled with surgical techniques to approximate equal leg lengths at skeletal maturity [3-5]. Historically, this has been done with a combination of acute lengthening and contralateral epiphysiodesis. Alternatively, allografts and cortical bone grafts, vascularized bone transfers, Ilizarov bone transport, and megaprostheses have been used [6-10]. Currently, several manufacturers offer options for prosthetic reconstruction with expandable implants. These implants are mostly desirable in the younger, skeletally immature, patients who will require multiple lengthening procedures [2]. Expandable implants can be expanded to a length projected on the basis of 3 factors: the length of bone resected, the anticipated future growth of the contralateral extremity, and the estimated discrepancy of leg length at skeletal maturity [11-16].

Prediction of the remaining bone growth

The epiphyses of the distal femur and proximal tibia contribute approximately 35% and 30%, respectively, to the growth of the lower extremity [3]. Resection of the distal femoral physis is associated with annual loss of approximately 1.6 cm [4] and continued normal growth of

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the contralateral lower extremity will result in significant leg length discrepancy at skeletal maturity [5].

The approach to a patient with a leg length discrepancy involves knowledge of: (1) the amount of growth which may occur in the long bones after various ages; (2) all of the equalization procedures, including their technical aspects and complications, to make a decision as to what method or combination of methods would most benefit the individual patient [17].

Growth estimates are typically done utilizing data compiled by Anderson et al. in percentile standard deviation charts. These charts show the growth remaining in normal distal femur and proximal tibia following consecutive skeletal age levels in relation to the standard deviation position derived from longitudinal series of 50 girls and 50 boys [18,19]. The relative maturity and various other factors in the prediction of growth are evaluated from the radiographic appearance of the bones in the hand and wrist, skeletal ages being read with the Greulich-Pyle Atlas [20]. Using the growth remaining charts, any number of calculation schemes can be used to estimate the anticipated growth in the contralateral limb and the expected growth loss from resection of an involved physis, and the physician can make decisions referable to equalization procedures [18,19]. Decision should be based on the patient's growth percentile and skeletal age; the percentage of growth inhibition over a given time interval (recommended minimum 3 months) is determined by the difference of the length of the growth minus the abnormal leg, divided by the length of the normal leg [17]. This is then used in conjunction with the growth remaining charts to determine the time of intervention [17].

Alternatively to Anderson et al. growth remaining charts [18,19], Fries [21] and Moseley [22,23] described different methods to evaluate the remaining bone growth. Fries converted the growth remaining graphs to straight line equations based on the fact that the expected growth due to the epiphyses about the knee is approximately linear up to the age of 15 in males and 13 in females [21]. Moseley described the straight line method, based on the concepts that limb growth can be graphically represented by a straight line and a nomogram relating limb lengths to skeletal age can provide a mechanism for considering the child's growth percentile and its relationship to the overall leg length discrepancy. By using this method, with manipulation of the growth lines, the equalization procedures can be visualized [22,23].

Expandable tumor prostheses

Expandable tumor prostheses with different expansion mechanisms have been used since the late 1970s. The first models had to be fully exposed during surgery, with the patient under anesthesia to perform the elongation; expansion was achieved by introducing a spacer, such as a ball bearing or serial sleeves. Adjacent physeal growth usually continued with polished stems since growth would pull cement-component interface apart [12,24-26]. In 1976, the Centre for Biomedical Engineering designed and manufactured the first expandable massive implant. This early version had a simple worm drive mechanism to extend the prosthesis [25]. The first expandable device widely used in the United States was the Lewis Expandable Adjustable Prosthesis (LEAP, Dow Corning Wright Corporation, Arlington, TN) introduced in 1983. The mechanism consisted of a fixed stem with a screw extension mechanism. Expansion was induced using a chuck key that turned the screw mechanism through a small incision. As the screw mechanism was advanced, the tubular portion of the construct moved and expanded the overall length of the prosthesis [12,24]. This technique had a high failure rate over the long periods of time required for multiple expansions in children [24]. As a result, more rigid mechanisms of expansion have been developed. One of the most common was the modular endoprosthesis developed by Stryker Howmedica Osteonics (Allendale, New Jersey). This prosthesis was not originally developed for expansion, but its modular design was suitable for this application. Removing the midsection of the prosthetic device through an open surgical procedure allowed the placement of longer midsections with a minimum lengthening of 2 cm at a time. This resulted in a much lower failure rate but also in an increase number of complications, particularly in the soft tissues [13,14,26].

Using first generation expandable prostheses, implant survival analysis with failure defined as having severe pain or undergoing revision or amputation showed a cumulative success rate of 93.9% at 1 year, decreasing to 65.2% at 5 years and to 0% at 10 years. On average, the overall functional outcome was estimated at 77% of the expected normal function. The cumulative 100% failure rate at 10 years illustrated the high level of complications encountered [27].

The second generation of expandable prostheses was minimally invasive; lengthening was achieved with an elongating screw or telescopic mechanism. Although they also required an open procedure, the need for soft-tissue dissection and complications were dramatically reduced, and motion was better preserved [28]. The minimally invasive Kotz Growing prosthesis was developed in 1987 by Kotz et al. [30]. The prosthesis matched the Kotz Modular Femur Tibia Reconstruction system (KMFTR®, Howmedica Modular Reconstruction System, Stryker, UK) and its successor, the fixed hinge HMRS® (Howmedica Modular Resection

System, Stryker, UK) and the rotating hinge GMRS® (Global Modular Replacement System, Stryker, UK) [30]. The growth module had an encapsulated elongation mechanism containing a threaded spindle driven by a bevel gear pair which moved a titanium sleeve by a threaded bush; adjustment was performed by unlocking a small fixation screw that gave access to an adjustable screw that allowed variable lengthening of the prosthesis by 1 mm per turn without the need for spacers [30]. When growth had ceased, the extendable module and the smooth anchorage part were replaced by the standard components of the KMFTR® or HMRS® prostheses. The disadvantages of this prosthesis, were the potential for failure of the expansion mechanism and failure of the prosthesis at maximal lengthening [11,31].

In the early 1990s, Biomet Corporation (Warsaw, Indiana) developed a more rigid expansion technique using a mechanically controlled telescoping device. Once extension was achieved, metallic blocks were placed in the telescoping pieces to hold them at the appropriate length. This had the advantage of requiring a less invasive surgical procedure to achieve expansions of 1-2 cm at a time rather than 2 or more [29]. The Stanmore® minimally invasive expandable prosthesis (Stanmore Implants, Stanmore Middlesex, UK) was a good option for patients reaching skeletal maturity, especially if the resection was relatively small. With its smaller volume, the implant was suited to the proximal humerus and proximal tibia, and required a small incision to lengthen the prosthesis. Once skeletal maturity has been achieved, the implant could be retained [25,28].

The third generation of expandable prostheses is the non-invasive type. The first designs were introduced in the 1980s [11,28,30,31]. In 1984, the Repiphysis® (Wright Medical Technologies, Arlington, TN) non-invasive expandable prosthesis, originally known as the Phenix Prosthesis (Phenix Medical, Paris, France) was developed for skeletally immature children [31]. First designed in France, the Phenix prosthesis consisted of two tubes with a spring mechanism buried in the larger tube. The spring was maintained compressed by a polyethylene locking mechanism. One tube was connected to the stem of the implant, and the second comprised the hinge portion of the hinge prosthesis. The uninvolved side of the joint was minimally resurfaced with a press-fit stem to attempt to preserve function of the non-involved growth plate. Expansion was achieved via exposure to an external electromagnetic field around the extremity. The coil produced heat in the center of the field. This was focused on the receiving antenna within the implant itself. This antenna was heated by the electromagnetic field. The heated element softened the surrounding polyethylene locking mechanism, which allowed spring expansion that pushed the two tubes apart from each other (Figure 1) [11,13]. In practice, 6-15 mm of lengthening was achievable at each expansion with this system [31]. As this expandable prosthesis was non-invasive, the risk of complications due to repeated surgeries were minimized. However, the inherent risk of complications due to the implant itself were too many [11,31-33].

The Stanmore® third generation non-invasive expandable implant (Stanmore Implants Worldwide, Stanmore Middlesex, UK) used electric current to produce a rotating magnetic field that was captured by a magnet within the implant and extended a gearbox [25]. The Stanmore® non-invasive expandable distal femoral prosthesis consisted of a femoral component, a constrained knee and a tibial component. Its design has changed over the last two decades. In the early types lengthening was achieved by insertion of ball-bearings

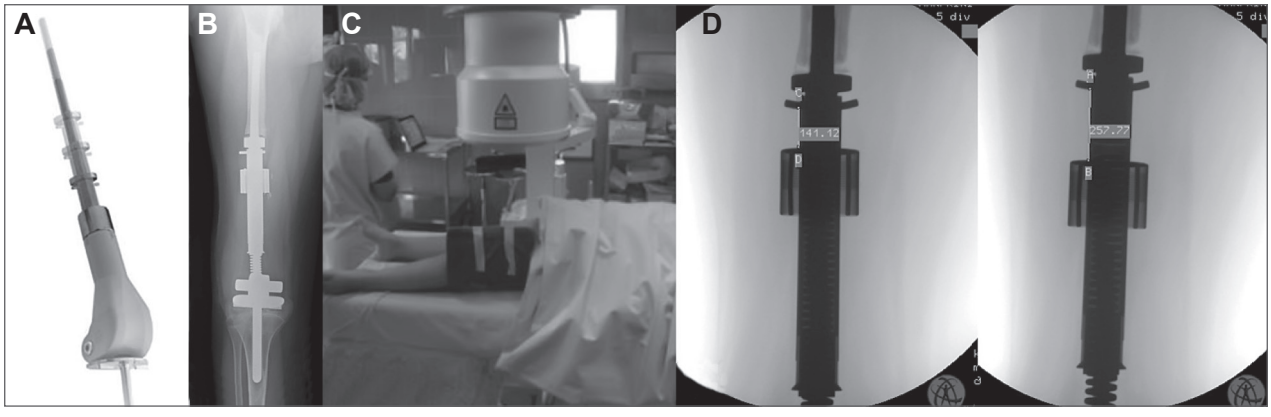

Figure 1. An 8-year-old boy with a distal femoral osteosarcoma. **(A):** Schematic presentation of the prosthesis, and **(B):** Anteroposterior radiograph of the femur and knee after limb-salvage surgery and reconstruction using the Repiphysis® expandable prosthesis. **(C):** Lengthening under general anesthesia using image intensifier. **(D):** Three lengthening procedures were performed obtaining a final total lengthening of 258 mm.

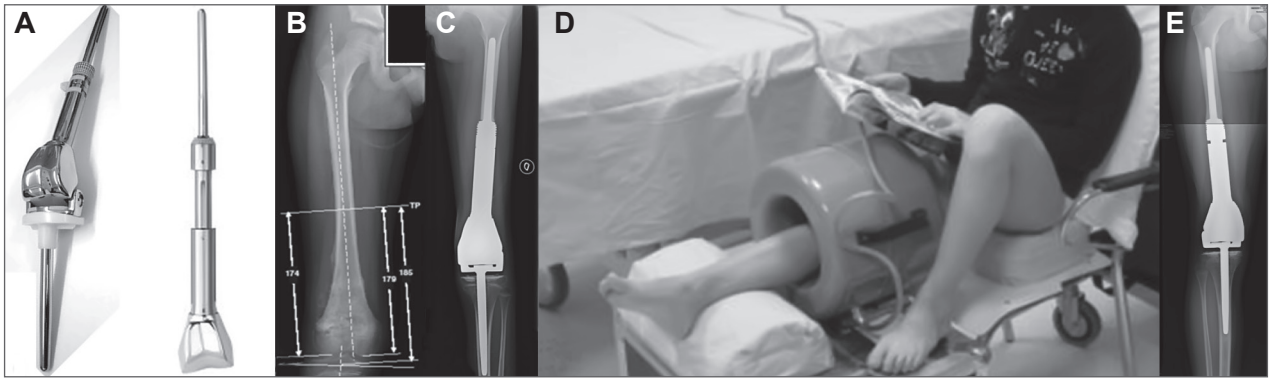

Figure 2. An 8-year-old girl with a distal femoral osteosarcoma. **(A):** Schematic presentation of the prosthesis. **(B):** Preoperative planning, and **(C):** Anteroposterior radiograph of the femur and knee after limb-salvage surgery and reconstruction using the non-invasive Stanmore® expandable prosthesis. **(D):** Lengthening at the patients' ward, without anesthesia using a rotating magnetic field. **(E):** Anteroposterior radiograph of the distal femur and knee after 5 mm lengthening.

and later by exchange of metal spacers (C-clips) of variable length. The more recent model (Extendable Mark V, Stanmore Implants Worldwide, Department of Biomedical Engineering at the Institute of Orthopaedics, Stanmore, Middlesex, England, UK) consists of a femoral component, a constrained knee and a tibial component that slides in a polyethylene sleeve. Expansion is achieved by electric current that produces a rotating magnetic field, which is captured by a magnet within the implant and extends a gearbox [27]. The tibial component is designed to preserve as much of the proximal tibial physis as possible. This allows the tibial component to slide in the polyethylene sleeve and growth to continue at the proximal tibial physis (Figure 2) [26,27].

The modular implant of the bioexpandable prosthesis MUTARS BioXpand device (Implantcast, Buxtehude, Germany) was presented in 2005 [9]. Based on the method of callus distraction, the bioexpandable system uses a lengthening nail as a modular part of the prosthesis to activate bone growth and lengthen the remaining bone. The mechanical, non-invasive system uses a miniaturized, mechatronic actuator inside the prosthesis which is activated by a high frequency transmission from outside the skin (Figure 3). The implant consists of a joint-forming part, a shaft substitute and an anchoring part within the remaining bone segment. The joint-forming part does not differ from conventional tumor prosthesis and is coupled with the corresponding joint surfaces. The shaft assembly is available in different lengths to bridge the bone defect resulting from tumor resection. An exchangeable shaft is used as an anchoring part to the bone and placed in the central cavity of these two prosthetic components. To avoid osteointegration, the shaft has a polished surface. Directly after tumor resection, a solid intramedullary nail is implanted as a spacer. Once a leg-length discrepancy resulting from normal contralateral growth of more than 3-4 cm is measured on postoperative follow-up, the solid intramedullary nail is exchanged for the active motorized lengthening nail and the bone undergoes cortical osteotomy; total elongation may reach 5 cm. After the lengthening procedure, the expandable components can be replaced by the regular MUTARS® components [9,34]. The third generation expandable prostheses have shown promising early results, but additional data are required about their long-term structural integrity.

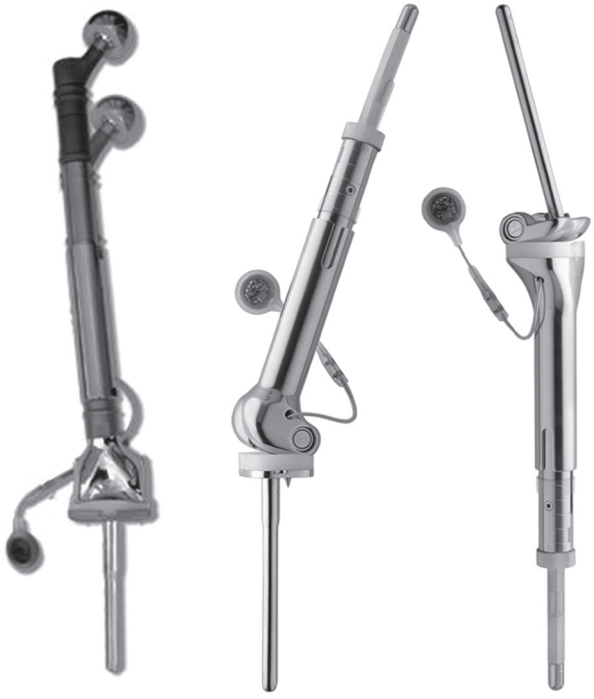

Figure 3. Illustration showing the total femoral (left), distal femoral (middle) and proximal tibial (right) MUTARS® expandable prosthesis.

For distal femoral expandable prostheses, on the tibial side, an intramedullary stem with a smooth surface is used to anchor the expandable prosthesis. This prevents bony ingrowth which might interfere with the activity of the growth plate, and has been shown to be effective in allowing about 80% of the normal growth of the proximal tibial physis to continue [26].

In the upper extremity, the proximal humerus is the fourth most common site for primary bone tumors. In younger children inequality of arm length cannot be justified, recommending the use of expandable prostheses in any child who may be left with 50 mm of discrepancy after resection of a tumor [35]. The major advantage is the high acceptance by the child and the parents, especially from the emotional and functional aspects. Progressive lengthening of these prostheses does not adversely affect the overall function of the arm, and superior subluxation of the head of the prosthesis has not been a problem [35,36]. Their main disadvantage was loss of controlled movements of the shoulder, especially significant loss of abduction and flexion. Elevation of the arm above the shoulder height was rarely possible unless the length of the bone resected was very short so that most of the muscles around the shoulder can be retained [35].

Lengthening

Postoperatively, at each visit, radiographs of the prosthesis are obtained. In children with non-invasive prostheses, when a discrepancy of 1-2 cm exists, lengthening is undertaken. Small lengthening of about 6 mm at each follow-up examination is recommended, although in carefully selected patients, lengthening up to 10 mm may be performed [36]. This allows immediate postoperative mobilization and avoids neurovascular complications due to overstretching of the soft tissues. Following lengthening, a radiograph using magnification markers is obtained to determine how much lengthening has occurred. Once the desired amount of lengthening is achieved, the process is stopped [2]. The risk of inadvertent lengthening of the prosthesis by standard MR imaging used for oncological follow-up is minimal, and MR imaging does not impair the functioning of the lengthening mechanism of the prosthesis [5]. The Stanmore® non-invasive expandable implants contain a magnet and therefore, once implanted, the patient must not be taken to the MRI scanner.

Results/Outcome

Early experience with expandable prostheses in children has been satisfactory in most series, offering the advantages of limb-salvage surgery in addition to total lengthening ranging from 4.25 to 55 mm, and good or excellent (>70%) Musculoskeletal Tumor Society (MSTS) function results at a follow up ranging from 12 to 152 months [11,15,29,37-39]. However, open lengthening procedures for the initial designs were accompanied with risk of joint stiffness, nerve damage and infection, and in some cases amputation [12-14]. In addition, re-operations to replace the expandable prosthesis with another expandable prosthesis for further leg lengthening as growth continues and revision surgeries for complications were far too many [11,37,38]. Moreover, some designs have been associated with an unacceptably high inherent risk of complications [11,29,31-33]. Approximately 25% of expandable prostheses had to be revised over the first 5 years for complications; at 10 years, the overall risk of developing at least one complication was up to 82% [1]. The complications were related to the fact that they are mechanical devices. Mechanical failure including aseptic loosening and metal fatigue, mechanical dysfunction of the expansion mechanism, soft tissue contracture especially around the knee, growth plate failures, dislocation and infection were the most common (Table 1) [11, 13, 26, 27, 29, 30-32, 37, 38, 40-42].

Aseptic loosening and mechanical dysfunction were common modes of failure and often necessitated one or more extensive revision surgeries. Even in well cemented prostheses, the strength of the forces generated by the child's activities resulted in loosening of the prosthesis and cement [29]. The moving parts of the prostheses were subjected to extensive wear, resulting in failures of the expanding mechanism, implant breakage, breakage of the clips holding the telescoping device, or failure of the plastic material in the newer all-polyethylene devices [29,31]. The development of a black-stained pseudocapsule surrounding the prosthesis, predominantly made of titanium, has been widely reported (Figure 4); the tubular scar with its smooth and glossy appearance was recognized as a fibroblastic response to titanium wear particles [12,30]. The rate of deep infection, most commonly for proximal tibia reconstruction, was between 25-40% [30,41]. The overall risk of the prosthesis becoming infected was 68% within 10 years. The risk of infection per procedure was 5.1% [1,27]. Although the amount of acute lengthening is usually conservative to avoid neurovascular complications and joint dysfunction, neurovascular compromise and loss of motion have also been reported [2,24]. Neurovascular compromise is minimal if lengthening is 2 cm or less [29]. Wound complications were reduced since minimally invasive or non-invasive lengthening procedures were performed. To avoid joint stiffness,

Table 1. Summary of studies on expandable prostheses in children

Study	*Expandable prosthesis*	*Lengthening procedures/ Mean total lengthening (mm)*	*Complications*	*MSTS function*
Neel et al. [11]	Repiphysis®	60/34	60% (aseptic loosening, breakage; arterial thrombosis-amputation)	Excellent
Eckardt et al. [13]	LEAP®, Repiphysis®, Howmedica, Techmedica prostheses	32/90	94% (loosening, infection)	Excellent and good
Cool et al. [26]	Stanmore®	–	21% (aseptic loosening, breakage, infection)	–
Schindler et al. [27]	Stanmore® (Mark II and III)	52/85	67% (aseptic loosening, breakage; local recurrence, infection-amputation)	Excellent and good
Schiller et al. [30]	LEAP, Kotz Growing prosthesis	53/131	35% (breakage, aseptic loosening, infection, wound dehiscence, patellar tendon avulsion)	Excellent and good
Wilkins and Soubeiran [31]	Repiphysis®	21/28	33% (breakage, infection)	–
Gitelis et al. [32]	Repiphysis®	58/38	39% (breakage, aseptic loosening, infection)	Excellent (ISOLS score)
Belthur et al. [37]	Stanmore® (Mark III, IV and V)	63/19.2	78% (aseptic loosening, malfunction of the expansion mechanism; local recurrence, infection-amputation)	Excellent
Gupta et al. [38]	Stanmore®	46/25	14% (knee flexion deformity)	Moderate
Haidar et al. [42]	Repiphysis®	42/31.5	67% (aseptic loosening, breakage, infection, wound dehiscence)	Excellent

MSTS: Musculoskeletal Tumor Society, LEAP: Lewis expandable adjustable prosthesis

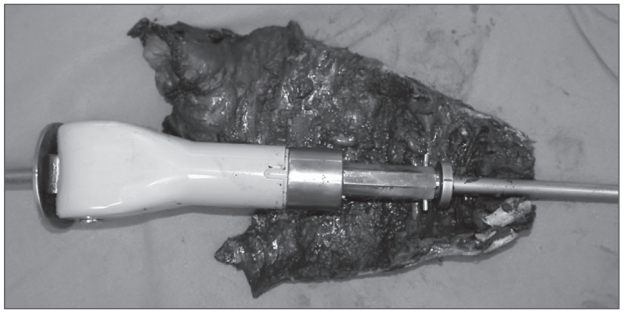

Figure 4. Intraoperative photograph of a revised Repiphysis® expandable prosthesis for mechanical dysfunction shows the black-stained pseudocapsule surrounding the prosthesis.

small lengthening of 6-10 mm per procedure, rehabilitation to address flexion contractures, and avoidance of further lengthening for at least 6 weeks if stiffness occurs is recommended [24].

Conclusion

Surgical treatment plans for correction of limb length discrepancies require an accurate assessment of limb lengths, prediction of future growth, and proper perspective of the treatment modalities available, viewed in light of the patients' and families' expectations. In the growing children who have met the adult criteria for limb-salvage surgery for bone sarcomas, expandable prostheses are worthwhile as a spacer to maintain equal limb length and a functional limb until the child achieves skeletal maturity. Currently, these designs are still under development but surgeons and manufacturers are optimistic that they will obviate most of the problems encountered in the past. Third generation expandable prostheses have shown promising early results, but additional data are required about their long-term structural integrity; however, the surgeons must keep in mind that the primary objective of treatment is to eradicate the tumor; this must not be jeopardized by overambitious attempts at limb reconstruction.

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