Reconstruction in orthopaedic oncology: frontier and horizon

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Abstract: Reconstruction is the essential part of limb-salvage surgeries for bone and soft-tissue sarcomas. With the progress in the past decades, abundant experiences have been accumulated in reconstruction for the proximal femur, the proximal humerus, the elbow, the knee and the pelvis. However, improvements of functional status and prevention of complications are still in need, which demands a theoretical system to instruct and evaluate new conception for reconstruction. To this aim, we propose the 'MAFOS' model, which are the initials of Materials, Articulation, Fixation, Osseointegration and Soft-tissue reconstruction. The 'MAFOS' model can guide us to inspect the rationality of new methods or designs, and thus can reduce the risk of reconstruction failure.

Keywords: Reconstruction; tumor; prosthesis

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Reconstruction of bony defect with satisfactory durability and function is an important issue for orthopaedic oncology. A huge progress has been achieved with emergence of many justified reconstruction methods (e.g., allograft, autograft, recycling tumor bone, rotationplasty, plating and nails, endoprostheses, spinal instruments) and endoprosthetic systems (e.g., KMFTR, GMRS, Stanmore, MUTARS) during the past four to five decades (1). Although abundant experiences have been gained in reconstruction for defects around the hip, shoulder, elbow, knee and acetabulum, optimization is still possible and demanded.

Where are we?

Proximal femur

Proximal femur is a common site for primary osteogenic sarcoma accounting for about 16% Ewing's sarcoma, 13% chondrosarcoma and 10% osteosarcoma (2). Proximal femoral replacement (PFR) has been the most popular and mature method for reconstruction after resection of the proximal femur because satisfactory functional status and high longevity of the implant are guaranteed (2-4). Complications are relatively rare. It was reported that the probability of a patient surviving aseptic loosening for 10 years was 93.8% (5). Dislocation of the hip has been a concern for PFR but the risk was low ranging from 2.7% to 5.7% (3,4). Augmentation of the hip capsule and abductors with artificial ligaments can further improve the stability and function of the endoprosthesis (6). Bipolar hemiarthroplasty is recommended but groin pain and acetabular erosion might occur. However, the risk is low and only about 5% of the cases would need conversion to total hip replacement during follow-up (3,7).

Proximal humerus

There are multiple reconstruction methods after resection of the proximal humerus (8,9). The prosthetic methods included proximal humeral replacement (PHR), allograft-prosthetic composite (APC), and the reverse total shoulder arthroplasty (rTSA), while the non-prosthetic methods included osteoarticular allograft, arthrodesis with different kinds of autografts, and Clavicula Pro Humero (CPH). Generally, PHR is the most common method because it is convenient to handle and provides satisfactory cosmetic appearance as well as acceptable function of upper limb (majorly the function of elbow and hand) (9,10). However, the function of the shoulder joint depends greatly on the function of deltoid and subluxation of the prosthesis is a common complication (11-13). Arthrodesis could achieve permanent stability once the bone heals, and then the motion of the arm can be improved via the movement of the scapula (14-16). However, the surgical procedure of arthrodesis is complicated and mechanical complications are not rare (9).

Elbow

The elbow is an uncommon site for primary or metastatic bone tumors (17). Reconstruction after removal of a peri-elbow malignancy has been very difficult due to the high stress at the articulation and high demand for range of motion. Total elbow replacement, either with segmental prostheses or allograft-prosthesis composite, has remained as a mainstream for reconstruction (17-19). The functional outcomes were satisfactory with a mean Mayo Elbow Performance Score (MEPS) ranging from 75 to 82, a mean Musculoskeletal Tumor Society (MSTS) score raging from 73% to 84% (17-20). The rates of complications, however, were always very high (24–65%) compared with the prostheses of the shoulder, hip and knee (19). Neuropathy (5–27%), infection (4–23%), nonunion of allograft (9–83%) and aseptic loosening (16–30%) were common types of complications (17-20). Although the physical linking of the humeral and ulnar components could prevent subluxation or dislocation of the joint, it would bear high stress causing bushing wear at the hinge and would also transmit the stresses to the implant-cement-bone interface leading to osteolysis and finally loosening of the stem (19,21).

Knee

Endoprosthetic replacement has become the most popular method for reconstruction after resection of tumors around the knee for decades (1,4,22). With the evolution of the technology and experiences of clinical application, modifications on the designs have been made to improve efficacy and longevity of the prostheses, which included the development of modular implants, the application of different fixation methods (cemented or cementless), and the switch from a fixed hinge to a rotating hinge (5,23-29). It was summarized in a systematic review that the mean 5-, 10-, 15-, and 20-year implant survival of distal femoral replacement (DFR) were 78.3%, 70.1%, 61.6%, 38.3%, slightly higher than that of proximal tibial replacement (PTR) (75%, 60%, 55.3%, 25.1%). Aseptic loosening (8.8%) and infection (8.5%) were the most common major complications in DFR, while in PTR, infection (16.8%) was the most threatening complication (30). Moreover, there is no solid evidence supporting that cementless fixation has superiority over cemented fixation in preventing aseptic loosening, or vice versa. Rotating-hinge mechanism might improve long-term implant survival and reduce bushing wear, but not necessarily prevented aseptic loosening compared with fixed-hinge mechanism (30). To develop a more durable knee endoprosthesis, efforts should be focused on reducing loosening and infection.

Pelvis

Limb-salvage surgeries for pelvic tumors have always been challenging because it requires removal of the tumor with a satisfactory margin while preserving a limb that would exert better function than amputation. The principles for reconstruction of pelvic defect include restoration of normal loading transfer and restoration of a functional hip. Reconstruction after type I/I+IV resection is not mandatory but recommended according to the literatures, because an unreconstructed iliosacral defect can result in Trendelenburg gait, proximal and medial migration of the acetabulum, leg length discrepancy and compensatory scoliosis during long-term follow-up (31-35). Common reconstructive methods include iliosacral arthrodesis with autografts or allografts, instrumental fixation such as screw-rod system, or combined (31-42). A peri-acetabular resection would surely demand for an active reconstruction to regain a functional hip with adequate stability (43). Biological methods such as arthrodesis, pseudoarthrosis, and hip transposition, have been reported to yield good function but are less used currently because of the prolonged immobilization, discrepancy of lower limbs and limited hip joint movement (32,42,44,45). Re-implantation of devitalized tumor bone with total hip replacement is also a feasible method but could not be used in case of massive bone destruction (46). Endoprosthetic reconstruction is a prior choice nowadays after decades of evolution through saddle prostheses, custom-made hemipelvic prostheses, icecream cone/pedestal cup prostheses and modular hemipelvic prostheses (47-51).

What can we learn from the past? The MAFOS model

Looking back at the past, we can summarize that five elements are required for a successful reconstruction method, which include Materials, Articulation, Fixation, Osseointegration, Soft-tissue reconstruction (we call it the "MAFOS" model).

Materials

Allograft, tumor-free autograft, recycling tumor bones and their combinations are common choice for biological reconstruction (52-54). Vitallium (CoCrMo alloy) and Titanium alloy have been the most popular materials for endoprostheses for several decades exhibiting good strength, durability and biocompatibility (1). In recent years, silver coating of the endoprosthesis has been applied and showed efficacy in reducing the risk of infection in some retrospective studies (55,56). Porous tantalum stocks have been also used instead of structural bone grafts for bone defects for non-neoplastic and neoplastic diseases with good midterm and long-term results (57-59). Carbon-fibre and PEEK might benefit oncological cases in terms of post-operative radiological evaluation but still need further clinical investigations to justify its efficacy and safety (60,61).

Articulation

Articulation is the key element of a megaprosthesis, which should provide adequate stability and range of motion. To fulfill this goal, the mechanical principles of human joints were extracted and translated into the designs of the prostheses. The mechanism for stabilization, the dimensions of motion, the impetus for movement, and the distribution and transmission of the stress, are all fundamental factors for considerations. Stability is the priority of an articulation, which could be fulfill by hardware machinery, hinge or locking mechanism, and ligamentous augmentation. Dimensions of motion sometimes would be reduced purposely in prosthetic design to obtain enough stability, such as the knee and elbow megaprostheses. In other cases, the reduction of dimensions of motion is due to the insufficiency of impetus (muscle strength), such as the shoulder and total femoral megaprosthesis. However, the improved stability by hardware mechanisms, which violates the nature of the human joint to some extent, will undoubtedly generate extra stresses in the articulation and fixation interface that finally causes bushing wear or loosening (e.g., knee and elbow megaprostheses).

Fixation

Fixation methods could be divided into extra-medullary and intramedullary fixation. Extra-medullary fixation generally means screws and plating, which is mostly used in biological reconstructions. Prosthetic design favors intramedullary fixation. Cementation and pressing-fit have been the two major methods for fixation of the intramedullary stem of megaprostheses for many years with relatively good outcomes (5,26,62,63). However, aseptic loosening/fixation failure remains as a constant risk increasing with time (30). Efficacy of the intramedullary fixation does not merely rely on the method itself, but also on the surgical technique of the surgeons, the matching between canal and stem, and the shearing stress on the stem. Augmentation with hydroxyapatite collar that inducing extra-cortical bridge might help decreasing risk of aseptic loosening (26). The fixation method of the Compress® prostheses is an innovation, which is secured with a stacked set of Belleville washers that functions as a spring producing an compressive force at the bone-prosthesis interface (64,65). However, new types of failures also occur making this new type of prosthesis fail to show obvious advantages over the previous ones (30,66).

Osseointegration

Osseointegration is probably the only way to achieve permanent fixation for reconstruction. Methods to achieve osseointegration include bone grafting and fixation, coating of intramedullary stem, and more recently tantalum and 3D-printed trabecular implants (43,52,57,63). 3D-printing technology could produce implants in any shape with a porous interface when needed. This attribute helps us to accomplish reconstruction for complicated bone defects.

Soft-tissue reconstruction

A proper reconstruction of soft-tissue attachments is of great benefit for protection, stabilization and mobilization of the megaprosthesis. Adequate coverage of the implants with soft tissue is essential for prevention of infection and

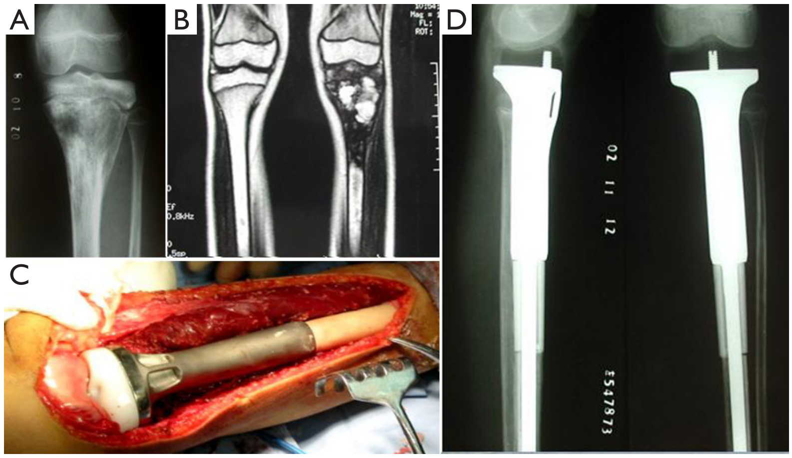

Figure 1 Application of proximal tibial prosthesis with a hemi-arthroplasty design. (A,B) A 12-year-old boy with osteosarcoma in the left proximal tibia. (C) He was treated with tumor resection and replacement with a proximal tibial prosthesis with hemi-arthroplasty. (D) Post-operative X-ray showed good alignment of the joint.

extrusion of the implants, which depends on the volume of residual muscle and fascia, and the size and contour of the implants. Sometimes a flap would be needed for safety. The reason why we oppose a contour reconstruction with metal prosthesis for bone defects is the difficulties for soft-tissue coverage. This is very important when designing prosthesis for pelvic defect as someone might want to precisely reconstruct the contour of the ilium wing, which is actually of little use but of great threat of soft tissue complications. Repair of the joint capsule and peri-capsular muscles are important for stabilization and mobilization of the megaprosthesis, which sometimes needs artificial ligament for augmentation (6,10). A little trick for soft-tissue reconstruction is to design some holes in the prosthesis for suturing.

Where to go?

Under the instruction of the MAFOS model, we have made some attempts on changing current designs of some common endoprostheses.

Innovation of articulation

For children with proximal tibial defects, we found that hemiarthroplasty with artificial ligament reconstructing collateral and cruciate ligaments could provide enough stability and excellent functional status (*Figure 1*).

For defects of proximal humerus with sacrificing the deltoid and axillary nerve, we have designed and applied a 3D-printed arthrodesis-type megaprosthesis (*Figure 2*). The megaprosthesis consists of three components including the glenoid component, the intermediate segment, and the humeral component. The contour of outer interface of the glenoid component is designed to fit the shape of the articular surface of scapular glenoid. It is porous with proper pore size and porosity that facilitates bone ingrowth. Assembly of the three components could easily achieve shoulder arthrodesis. The functional outcomes were excellent with the mean MSTS-93 score as 25.4±2.1, the mean forward flexion of 78.0°±13.0° and abduction of 62.0°±11.5°, in a preliminary cohort of 9 patients.

The advent of 3D-printing technology grants us more freedom for prosthesis design as it could produce implants in any shape. Straightforward duplication of the bone with metal is not feasible for many cases, but for the elbow joint, things may be different. We hypothesize that for the defect of distal humerus, hemiarthroplasty with a 3D-printed distal humeral endoprosthesis, which is designed according to the DICOM data of the contralateral humerus with mirror conversion, and reinforcement with artificial ligaments could provide enough stability and range of motion but less shearing stress on the intramedullary stem (*Figure 3*). Application of this method in a preliminary cohort of 5 patients has been resulted in satisfactory functional status and no major complications.

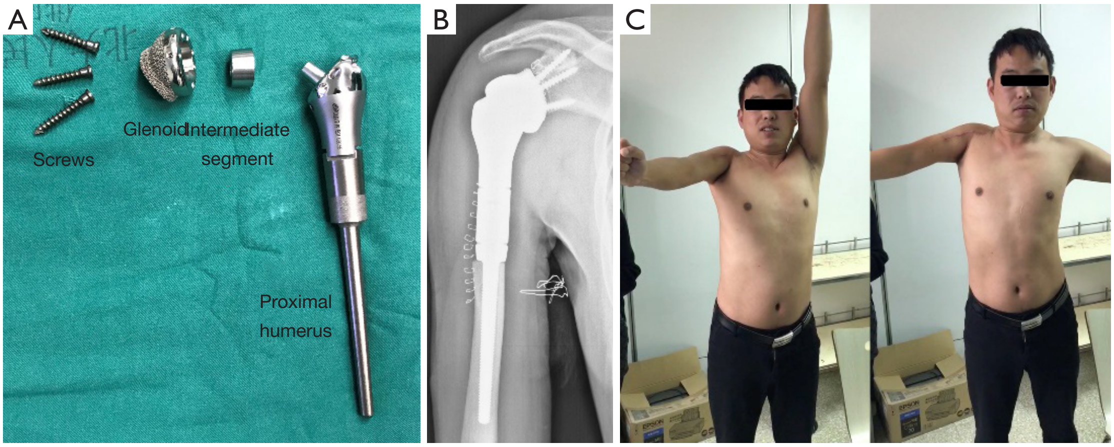

Figure 2 Application of a 3D-printed arthrodesis-type proximal humeral prosthesis. (A) It consists of three parts: the glenoid component, the intermediate segment and the humeral component. (B) After fixation of the glenoid component to the glenoid by screws, fixation of the humeral component by cementation, and assembly of the three parts by Morse taper, the defect of proximal humerus is reconstructed with shoulder arthrodesis. (C) A 30-year-old man diagnosed as malignant myoepithelioma in the right proximal humerus was treated with tumor resection and replacement with this arthrodesis-type prosthesis. The patient showed satisfactory functional status of the right shoulder 3-month postoperatively with an MSTS-93 score of 27.

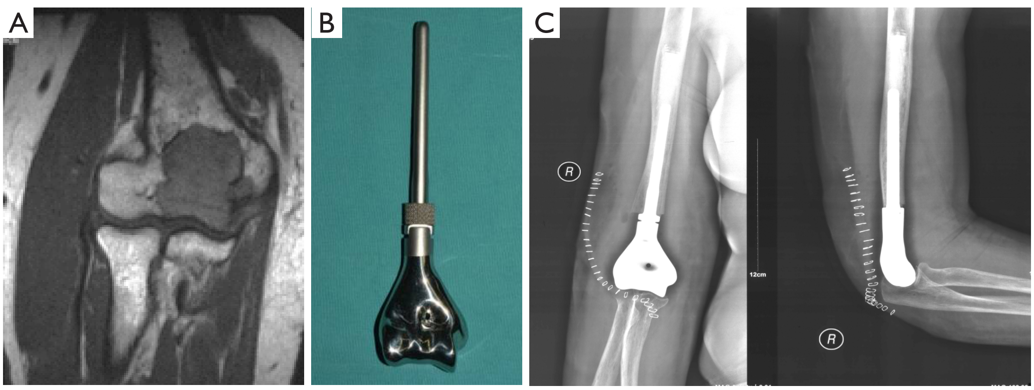

Figure 3 Application of 3D-printed distal humeral prosthesis with hemiarthroplasty. (A) This is a 61-year-old woman diagnosed with solitary metastasis of renal cell carcinoma in the distal humerus. (B) She was treated by en bloc resection of the tumor and replacement with a 3D-printed distal humeral prosthesis with hemiarthroplasty. (C) Post-operative X-ray showed good matching of the joint.

Refinement of fixation

Again, new technology such as 3D-printing technology could refine the fixation of megaprostheses. For instance, we improved our previous modular hemipelvic prosthesis with 3D-printing technology, not only to fit the outer curved surface of the residual ilium more perfectly, but also to provide precise screw path from the implant through the sacroiliac joint into the body of S1 and S2 (*Figure 4*) (43). Fixation through the sacroiliac joint could transfer the weight loading like the normal pelvis and could avoid dissociation of the sacroiliac joint compared with the previous prosthesis.

Glamour of osseointegration

3D-printing technology could produce implants with a trabecular interface that could facilitate bone ingrowth. A retrieval study of a 3D-printed hemipelvic prosthesis in our center proved that new bone could grow into to the

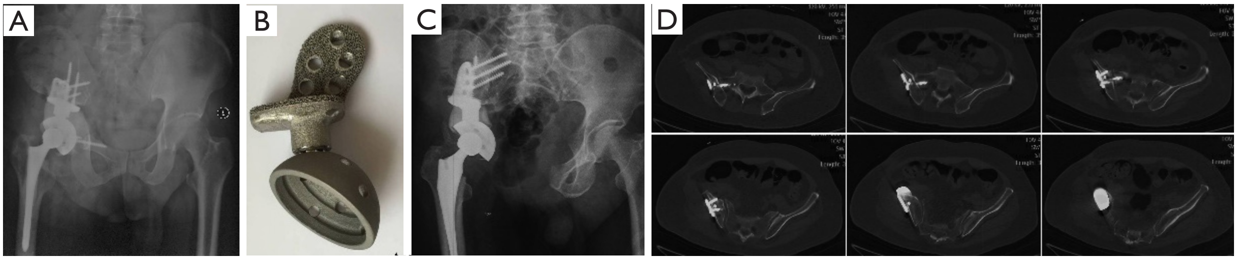

Figure 4 Application of a 3D-printed hemipelvic prosthesis for type II or type II+III resection. (A) This is the first generation of a modular hemipelvic endoprosthesis used for periacetabular defect, which was fixed at the iliac wing. (B) With the application of 3D-printing technology, we modified the previous reported modular hemipelvic endoprosthesis in terms of iliac foundation contour, fixation method and porous structure at the interface. (C) The 3D-printed hemipelvic endoprosthesis fit more closely to the outer lamella of the ilium and can be fixed with screws through the sacroiliac joint. (D) Sectional CT films show that the 3D-printed prosthesis could be fixed to the sacrum through the screw passages in the prosthesis (upper), while the previous prosthesis could only be fixed to the iliac wing (below).

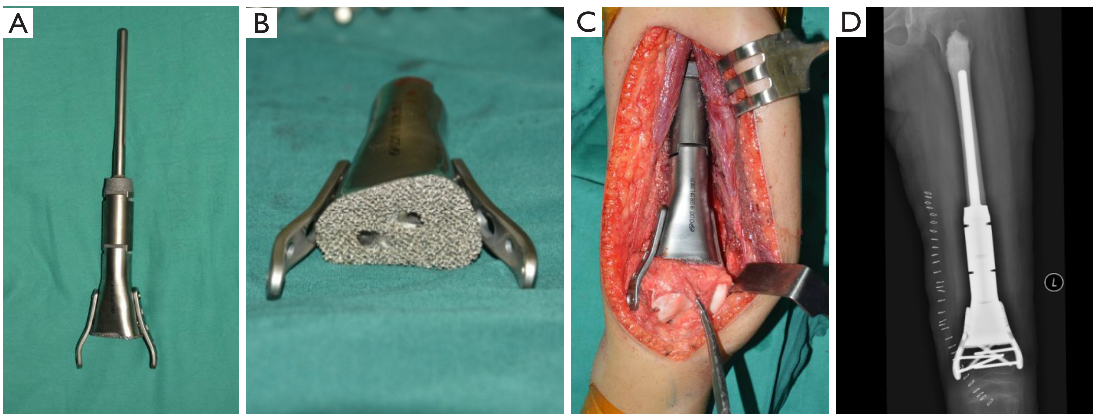

Figure 5 Application of a 3D-printed intercalary endoprosthesis for joint-salvage surgery. (A) This was a 3D-printed intercalary prosthesis with plating augmentation. (B) The interface to the bone was of porous structure that facilitates osseointegration. (C) Intra-operative photograph showed good matching between the prosthesis and the osteotomy plane. (D) Post-operative X-ray showed good fixation of the prosthesis.

porous structure (67). Using the 3D printing, we have achieved several difficult reconstructions for intercalary defects that could not be reconstructed with commercial modular prostheses (*Figures 5-7*). Post-operative follow-up showed that all of them achieved satisfactory bone ingrowth. Despite the efficacy of 3D-printed trabeculae for osseointegration, it should be kept in mind that factors affecting bone union would definitely affect osseointegration into the prosthesis. A stable fixation, an interface as large as possible, a constantly compressive stress at the interface, and a proper porosity rate and pore size would undoubtedly benefit osseointegration.

The advent of new materials, new technology and new surgical techniques might bring in chances and new ideas to improve current methods for reconstruction in the field of orthopaedic oncology. However, we should remain sober and rational when developing new methods for reconstruction. Careful evaluation of the reconstruction plan and implant design with the "MAFOS" model is required before clinical application. Does the material have appropriate mechanical properties and osseointegration potential? Can we attain a stable and functional joint? Is the fixation durable enough? Is the soft-tissue reconstruction satisfactory? If all yes, then a successful reconstruction is guaranteed.

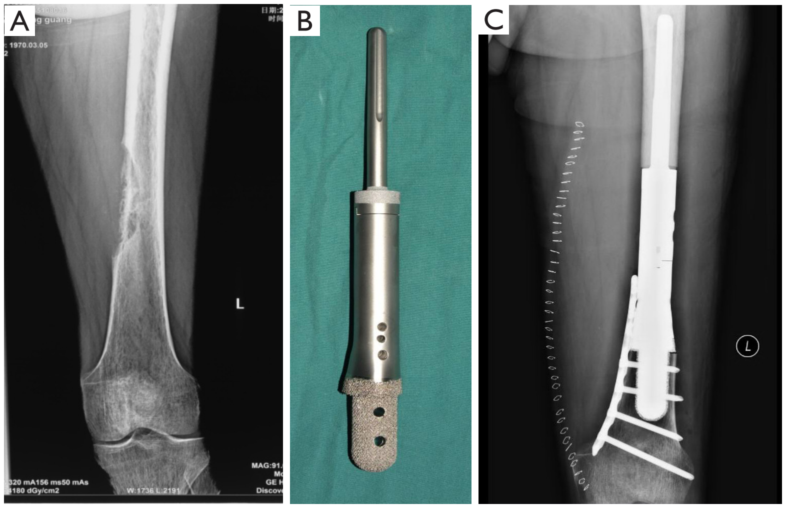

Figure 6 Application of a 3D-printed intercalary endoprosthesis for femoral defect. (A) A 48-year-old man was diagnosed as Ewing sarcoma at the diaphysis of the femur. (B) We designed a 3D-printed intercalary prosthesis with plating augmentation for femoral defect. The interface of the distal stem was of porous structure that facilitates osseointegration. There were two screws passages in the distal stem used for interlock with the plate. (C) Post-operative X-ray showed good fixation of the prosthesis.

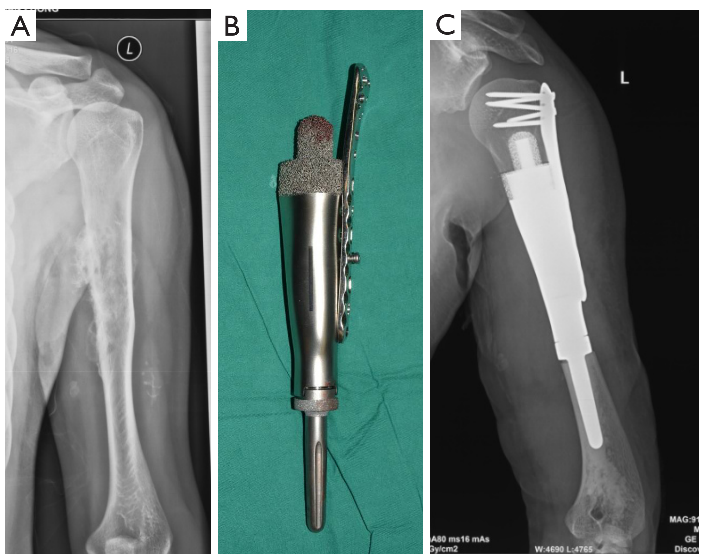

Figure 7 Application of a 3D-printed intercalary endoprosthesis for humeral defect. (A) A 30-year-old man was diagnosed as osteosarcoma at the diaphysis of the humerus. (B) We designed a 3D-printed intercalary prosthesis with plating augmentation for humeral defect. The interface of the proximal stem is of porous structure that facilitates osseointegration. (C) Post-operative X-ray showed good fixation of the prosthesis.

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Footnote

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