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Composite artificial semi-knee joint system

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Abstract. – OBJECTIVES: The purpose of the study was to investigate the clinical implantation protocol of custom-made artificial semi-knee joint based on computer-aided design so as to improve the limb salvage efficiency.

MATERIALS AND METHODS: The custom-made artificial semi-knee joint was designed and manufactured based on rapid prototyping technology. The repeated modifications were carried out in the design and manufacture of the semi-knee joint, together with the operation protocol. Clinical trial was conducted on 2 cases of osteosarcoma, one receiving allograft prosthesis composite transplantation, and the other receiving synthetic bone graft prosthesis composite transplantation. The clinical outcomes of the 2 patients were evaluated.

RESULTS: The custom-made artificial semi-knee joint met the clinical customization needs. In clinical trial, 18-month follow-up demonstrated the satisfactory knee joint function recovery in near future.

CONCLUSIONS: The custom-made artificial semi-knee joint based on computer-aided design can afford satisfactory knee joint function recovery following allograft bone transplantation.

Key Words:
Custom-made, Semi-knee, Synthetic bone, Limited contact, Nail.

Introduction

Considering the developmental characteristics of adolescents, limb salvage surgery for malignant bone tumors in children has been a tough problem in the tumor orthopaedics field. Many aspects are worthy of improving: (1) minimizing the postoperative limb length discrepancy; (2) selecting appropriate bone reconstruction materials; reserving the postoperative joint function. This paper describes the design and manufacture of custom-made artificial semi-knee joint based on computer-aided design (CAD) and rapid prototyping technology (RP). The accurate physical replicas of the articular surface between femur and tibia were harvested. Allograft prosthesis composite (APC) and synthetic bone graft prosthesis composite (SBPC) transplantation accomplished favorable biological reconstruction post removal of bone tumor. The outcome in clinical experiments proved satisfactory in the near future. The result provides an alternative approach to improve the clinical outcome of young patients with malignant bone tumor following limb salvage surgery.

Materials and Methods

Design of Artificial Semi-Knee Joint System

Design of Artificial Semi-Knee Joint

The principles for design of artificial semi-knee joint outline: The outline of the artificial semi-knee joint resembles the outer face of the joint needing reconstruction, ensuring the optimal matching effect to the contralateral articular surface. Computer tomography was utilized to obtain the point data. After deleting the mixed points, filtering the noise, sorting, smoothing, and screening the data, the reserved data were inputted into Surfacer 9.0 image processing soft var. Then, the 3D contour image of the knee joint was reconstructed according to the geometric characteristics of the original joint surface[1]. The obtained data representing the knee joint surface were applied to CAD of custom-made artificial knee joint, using UG software in IGES format (Figure 1).

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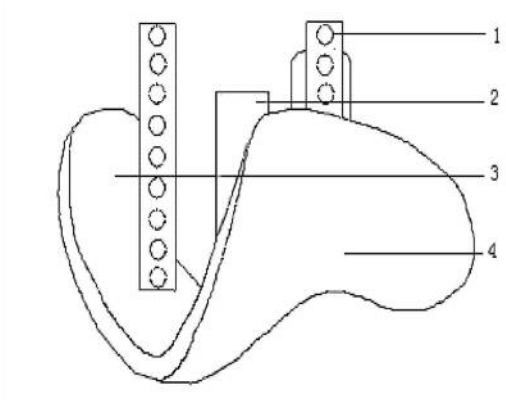

Figure 1. Diagram of design of custom-made artificial femoral condylar joint. 1, The special metal cages made of 2 dadoes and bone grafting in the cages. 2, The combining plate of the artificial semi-knee joint and the intramedullary pin. 3, A good match between the inner face of the artificial semi-knee joint and the outer face of the subchondral bone of allograft bone. 4. A good match between the outer face of the artificial semi-knee joint and the outer face of the femoral condylar articular cartilage.

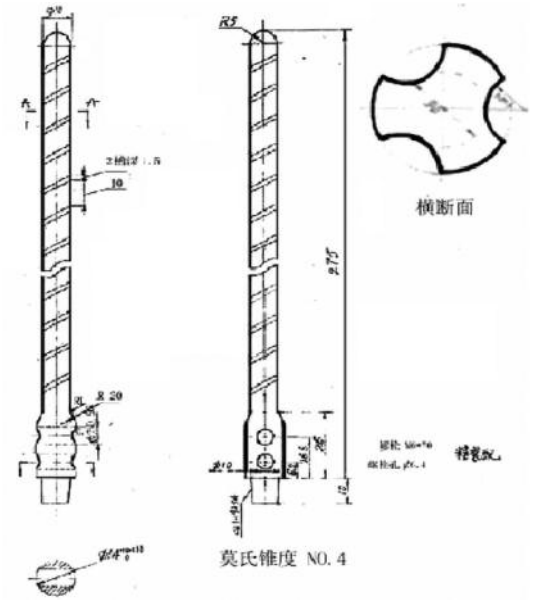

Figure 2. Engineering drawing of the intramedullary pin.

Design of Intramedullary Pin

The transverse section of the intramedullary pin was in the shape of clover, with three longitudinal gabs (recesses) throughout the whole lengthways, 1.5 mm deep, the width accounting for 1/6 of the perimeter of the intramedullary pin. The intramedullary pin was full of the oblique recesses in screw thread pattern throughout the whole lengthways, 1.5 mm deep, at the interval of 10 mm. The keyhole at the distal end possessed the screw thread structures internally, enabling the tight connection with the lockpin. The proximal end, without keyhole structure, was fixed with an anti-rotating screw inserted into the longitudinal gabs through the cortical bone at one side. The head part, in bullet head shape and 1 cm long, connected with the intramedullary rod by the screw thread structures, while the intramedullary rod connected with the hairline, also by the screw thread structures (Figure 2).

Design of the Synthetic Bone

The principles: The designed synthetic bone was the accurate replica of the patient topography to be produced, accomplishing a satisfactory matching to the repairing part of human bone defect. Simultaneously, the interconnection system and microcirculation system should be established inside the synthetic bone, allowing for the ingrowth of the cells and tissues inside the biomaterials, and providing enough nutrition to enable the formation of the functional tissues. The prismatical and dense ceramic enhancer was installed inside the synthetic bone to facilitate its mechanical strength. Depending on the data designed on the distribution density and size of the tubules, three-dimensional network frame was prepared by rapid prototyping technique, which would disappear through gasification during the formation of the synthetic bone, and the left space becomes the tubule system inside the prosthesis. There were porous microstructures inside the prosthesis with the interconnections between the pores, namely microcirculation system. The plastic particles were partially melted by heating or other chemical methods, or were shaped into the porous frame through adding adhesive materials. The adhesion environment and time could be regulated to control the size of the adhesion spot, namely the future interconnection between the pores (Figure 3).

Fabrication of the Artificial Semi-Knee Joint System

Manufacture of the Artificial Semi-Knee Joint System

Titanium (Ti6A14V) was used as the native material, and the fabrication was based on the

Figure 3. The imitation drawing of the artificial bone contratype.

combination of rapid prototyping (RP) technique and traditional casting craft. Briefly, after being converted into RP data format, the computer-aided design was imported into the rapid prototyping machine, and the prototype was achieved. Then the RP model was used as a positive mould to manufacture Ti6A14V alloy artificial semi-knee joint through ordinary mould-melted founding process (Figure 4). The intramedullary pin was prepared simultaneously through mechanical approaches.

Manufacture of the Synthetic Bone

The RP model was achieved on rapid prototyping machine. Then the RP model was used as a positive mould to build up a negative mould, into which pure tricalcium phosphate suspension was poured. The mould took form by drying, and developed into the porous structure through gasification and baking at high temperature. The wire frame of the negative mould consisted of resin, which developed into the tubules after baking at high temperature, ensuring the formation of the double circulation systems, microtubule system and microcirculation system, inside the synthetic bone (Figures 5, 6).

Animal Experiments

During the former period, pig was used as the animal model, whose knee joint structure was relatively similar to that of the human body. The femoral medullary canal was vertical, with the approximately same diameter as that of the human being. But the postoperative fixation was quite difficult, and the rehabilitation exercise was not enough. So there was poor satisfaction. During the middle and later periods, dog was instead used as the animal model, and the outcome was considered comparatively satisfactory.

The protocol of the animal experiments: The experiments were divided into three stages according to the time sequence: stage I, II, and III, as shown in Table I.

The results of the animal experiments are shown in Table II.

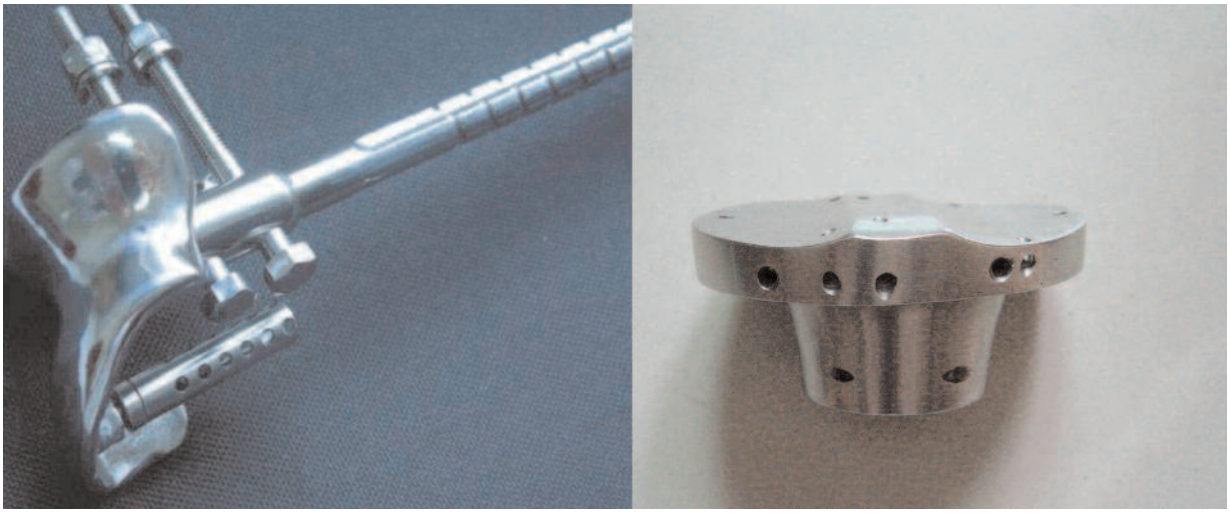

Figure 4. Artificial semi-knee joint system.

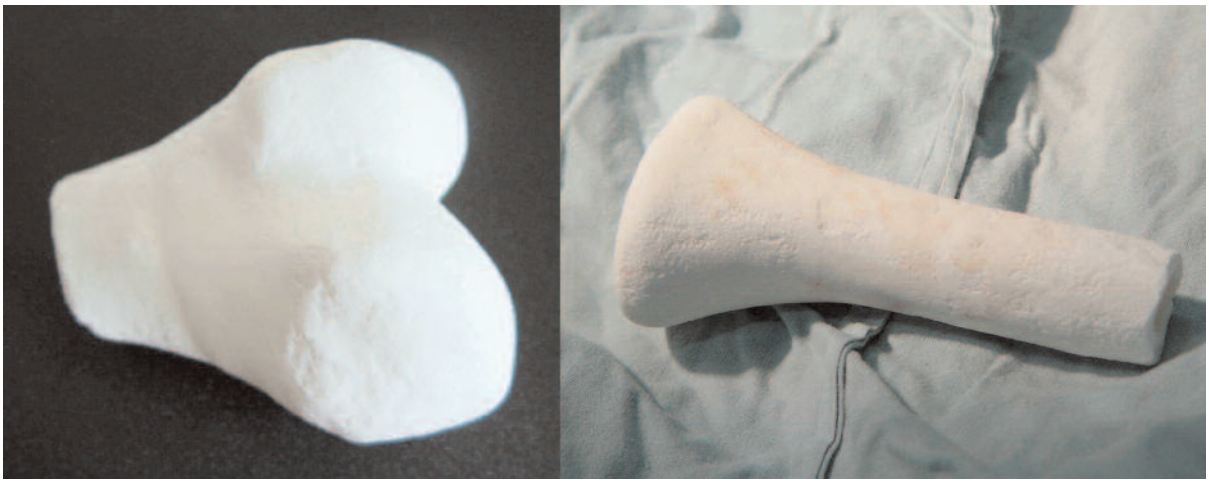

Figure 5. The entity of artificial bone.

Clinical Trials

Two patients were enrolled in the study. The first patient, male, 14 years old, was hospitalized for recurrence of osteosarcoma at right inferior-femur segment (Figure 13). The prosthesis was manufactured according to the data obtained by spiral CT scanning. After routine chemotherapy, the tumor was removal and repaired through combined transplantation of artificial femoral condylar joint prosthesis and APC based on rapid prototyping technology. Routine postoperative anti-infection and chemotherapy were performed.

The bone tumor at the inferior femur segment was removed completely. Application of artificial condylar cartilage joint prosthesis improved the matching between the allograft bone and the opposite joint. The medial and lateral accessory ligaments and the anterior cruciate ligament were also repaired. The operated limb was fixed with plaster stone for 6 weeks postoperatively. The patient carried out the rehabilitation exercises after removal of the plaster stone and was followed up for 18 months postoperatively.

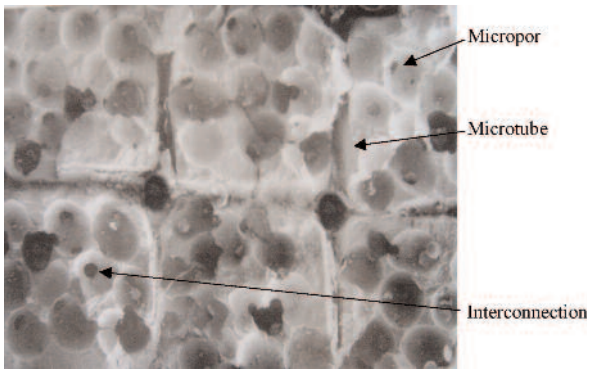

Figure 6. The electron microscopy observation of artificial bone.

1. No red or swelling of the skin, no hydrops and no pains were observed for the joint prosthesis. The wound healed satisfactorily.

Table I. General protocol of animal experiments (Figures 7 to 10).

Time	Animal model (n)	Body weight	Surgery Protocol	Intraoperative fixation	Postoperative fixation
Stage I	Pigs (7)	75-85 kg	APC	Intramedullary pin	Plaster stone
Stage II	Dogs (8)	20-25 kg	APC	Lockpin+bone Cement+bone Plate	Plaster stone
Stage III	Dogs (5)	20-25 kg	Prosthesis	Lockpin+bone cement	Plastic orthosis

Table II. Results of the animal experiments (Figures 11, 12).

Evaluation index		Stage I (pigs)	Stage II (dogs)	Stage III (dogs)
Survival		5 survived, 2 died of postoperative infection 2 weeks postoperatively	6 survived, 2 died of infection	5 all survived
Outcome	Postoperative nursing	Postoperative fixation was difficult. Rehabilitation exercise was not enough.	Cut was subject to split open and infection, needing repeated suture	The nursing was simple due to application of specific supporter
	Function recovery	Rest in quietude. Unobvious function recovery	Limping at various degrees. 2 suffered serious leg crimping	All were able to stand up. Limping was negligible.
	Joint moving ability	Poor joint moving ability	Active flexion and extension: 85°passive flexion and extension: 100°	Accurate implantation site
X-ray films	Implantation site of the joint prosthesis	Accurate implantation site	Improper implantation site in 3 cases. The prosthesis was away from femoral condyle	Accurate implantation site
	Matching degree of the joint prosthesis	A good match between the inner face of the joint prosthesis and femoral condyle of allograft bone, and between the outer face of the joint prosthesis and tibia joint surface at opposite side at opposite side	A poor match between the inner face of the joint prosthesis and femoral condyle of allograft bone, and between the outer face of the joint prosthesis and and tibia joint surface at opposite side	A good match of the inner face of the joint prosthesis and femoral condyle of allograft bone, and between the outer face of the joint prosthesis tibia joint surface at opposite side
	Joint space	Normal	Normal	Normal
Histological examination 3 months postoperatively	Signs of abrasion	Fibrous tissues formed surrounding the knee joint due to less rehabilitation exercise. It was meaningless to check the abrasion	Tibia corresponding to femoral condyle wore, more serious inner than outer. Tibia platform wore out in 2 cases	Tibia corresponding to femoral condyle wore a little, more serious inner than outer.

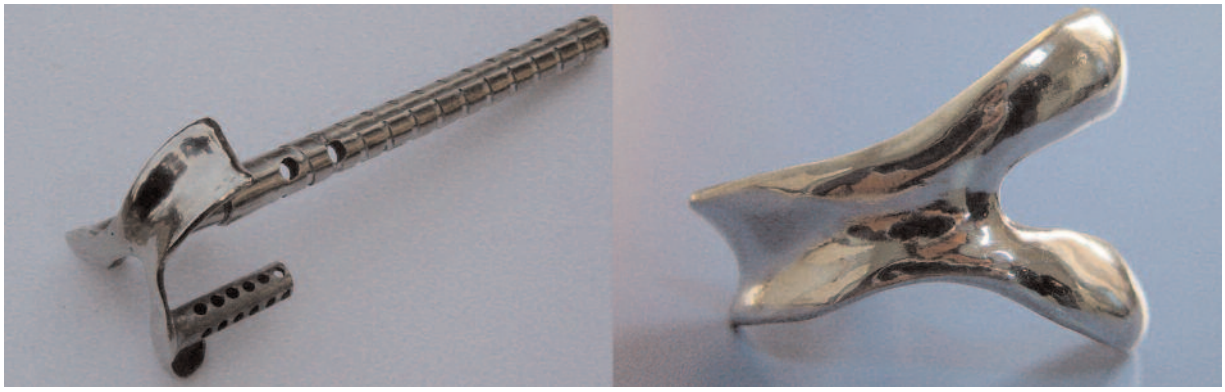

Figure 7. The experimental semi-knee joint prosthesis at different stages.

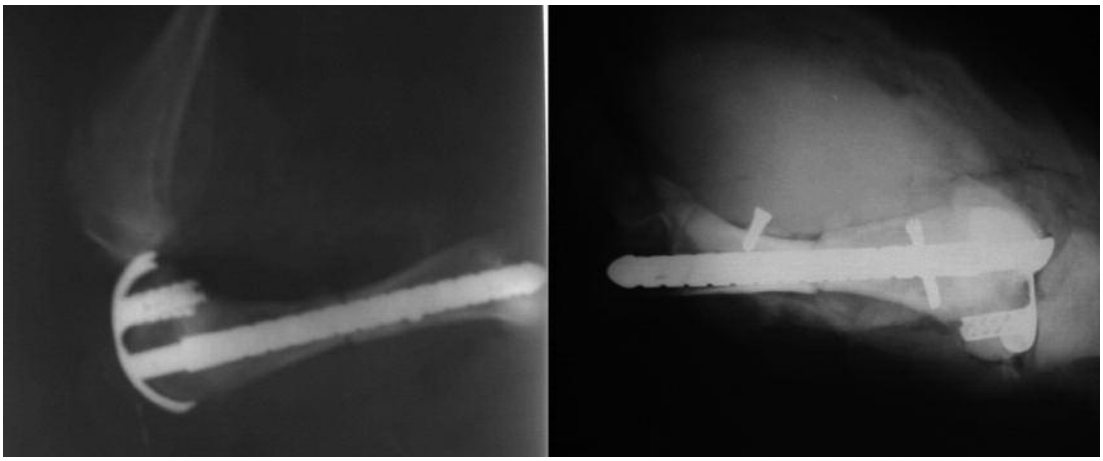

Figure 8. Postoperative X-ray examination at stage I.

2. Postoperative serial X-ray films did not demonstrate any disfiguration, loosening, and break of the artificial joint. The joint space existed. The internal fixation was effective.
3. The patient had normal gait and reported no pain in inferior extremity. The passive, active flexion and extension ranged 0-135°. The joint had good stability, with no any sideway translocation.
4. Right femur became thickened. Both orthotopic and lateral position X-ray films demonstrated newly formed bone along the intramedullary pin, named "endogenous callus surrounding the intramedullary pin". The newly formed bone density was even and crossed the epiphysis space and fused with the allograft bone (Figure 14).
5. Compared with the opposite side, the joint space did not become narrow. The osteoepiphysis did not disfigured. The tibia developed normally. The limb length discrepancy was 38.33 mm after 1 year follow up. No osteoarthritis symptoms and absorption line under the artificial prosthesis were observed (Figure 15).
6. General bone scanning and CT-PET examination demonstrated some catabolic activities of the APC, and confirmed the "endogenous callus surrounding the pin" as the newly formed bone after 1 year follow up (Figures 16, 17).

The second patient, female, 14 years old, was hospitalized for osteosarcoma at left superior tibia segment. The prosthesis was manufactured

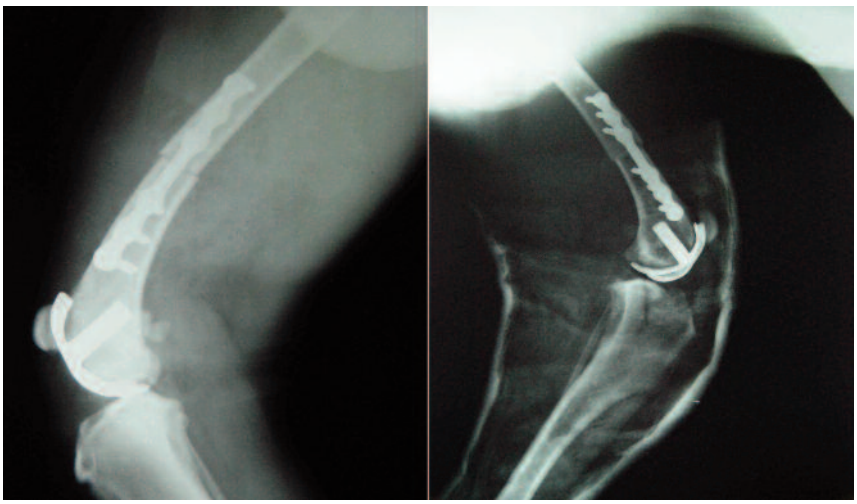

Figure 9. Postoperative X-ray examination at stage II.

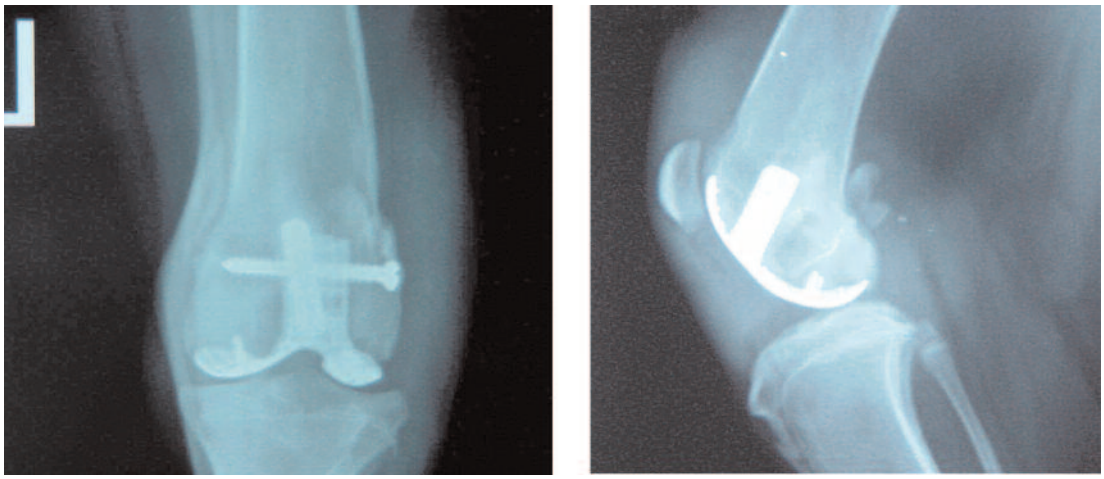

Figure 10. Postoperative X-ray examination at stage III

Figure 11. Harvesting materials at stage II.

according to the data obtained by spiral CT scanning. After routine chemotherapy, the tumor was resected from left superior tibia segment under general anesthesia. The defect following tumor removal was repaired through combined transplantation of artificial tibia condylar joint prosthesis and SBPC. Routine postoperative anti-infection and chemotherapy were performed (Figures 18, 19). Unfortunately, the follow-up of this patient was disrupted three months after operation for some reason.

Discussion

Evaluation of the experimental Animal model

In this study, semi-knee joint replacement was carried out. We aimed to investigate the feasibility of custom-made artificial semi-knee joint and the

Figure 12. Harvesting materials at stage III.

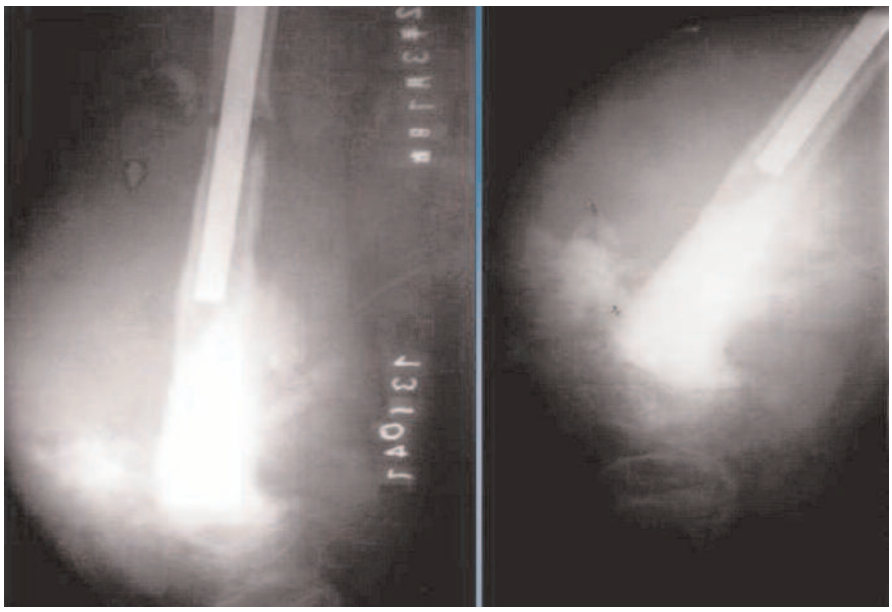

Figure 13. X-ray examination before operation.

aiding equipments in clinical surgery, the matching satisfaction and the abrasion of the semi-knee joint to the opposite joint cartilage and the niscus, and the histocompatibility of the Ti6A14V alloy. So it was significant to establish the suitable animal models.

At stage I, considering the resemblance of pig knee joint to that of human body, we carried out the internal fixation with the intramedullary pin, and the outcome was satisfactory. X-ray films revealed the proper implantation site of the prosthesis. The results guaranteed the future successful clinical performance of combined transplantation of allograft bone and artificial joint prosthesis.

At stage II, we carried out the fixation with bone cement, lockpin and bone plate together. The hairline was not applied, so a little deviation away from the accurate site occurred during the implantation. The outcome of the fixation with bone plate was less satisfactory than that with intramedullary pin.

At stage III. to avoid the serious surgical trauma resulting from allograft implantation in experiments at stage I and II, the joint prosthesis was directly implanted. Postoperative X-ray films displayed the accurate implantation site and the good matching between the inner

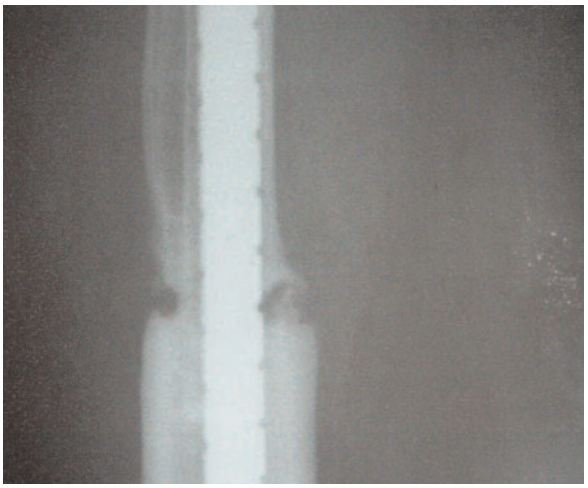

Figure 14. The synosteosis position after 18 months.

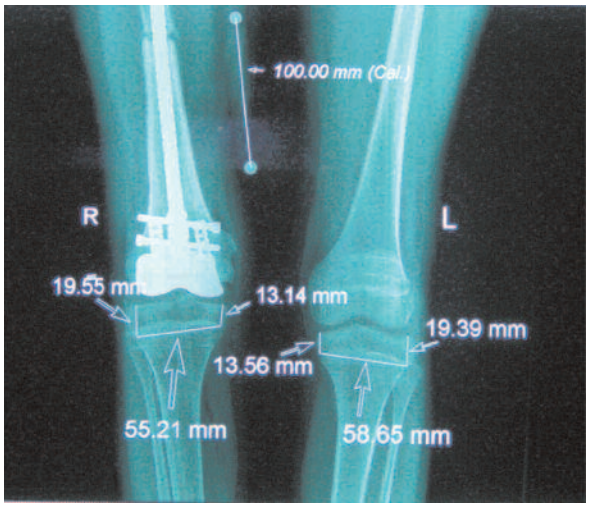

Figure 15. The osteoepiphysis and joint space after 18 months.

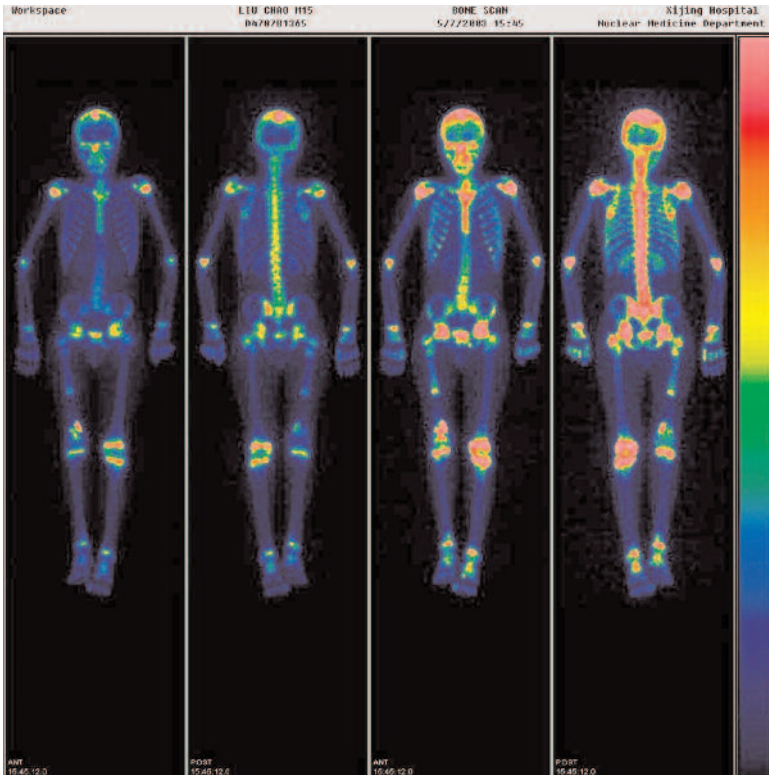

Figure 16. The general bone scanning after 1 year.

face of the joint prosthesis and the femoral condyle of the allograft bone, and between the outer face of the joint prosthesis and tibia joint surface at opposite side.

Design of the Semi-Knee Joint

Clinically used artificial knee joints, including customized joint prosthesis characterizing specific tumor, were unexceptionally whole joint prosthesis. For osteosarcoma, generally occurring at one side of the joint, and likely in adolescent whose osteoepiphysis has not been mature, whole joint replacement protocol, inevitably influencing the osteoepiphysis growth at the opposite side, is obviously unsuitable. Additionally, the customized joint designed for specific tumor requires hinge like joint replacement following removal of the bone segment suffering tuner, leading to the unsatisfactory attachment for surrounding soft tissues, which also limits joint moving ability. With the technical advances in chemotherapy and immunotherapy, the patient survives longer, and the prosthesis loosening is attracting more and more attention. Besides, the reconstruction of the bone defects with allograft bone and artificial joint prosthesis following removal of bone tumor at superior femur segment has shown promising outcome[2], which has been the generally accepted surgery protocol worldwide. The knowledge arouses great enlightenment for our team.

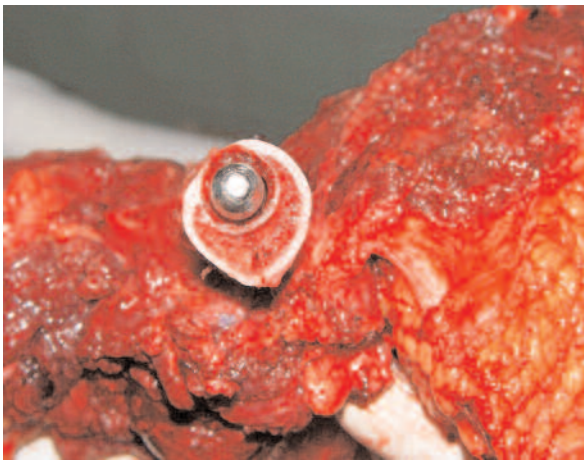

Figure 17. Endogenous callus surrounding the intramedullary pin.

In this paper, we designed a new type custom-made semi-knee titanium alloy joint cartilage prosthesis based on the rapid prototyping technique, which might be also applied to transplantation of bioengineering bone graft[3]. Crucially, a good match of the inner and outer

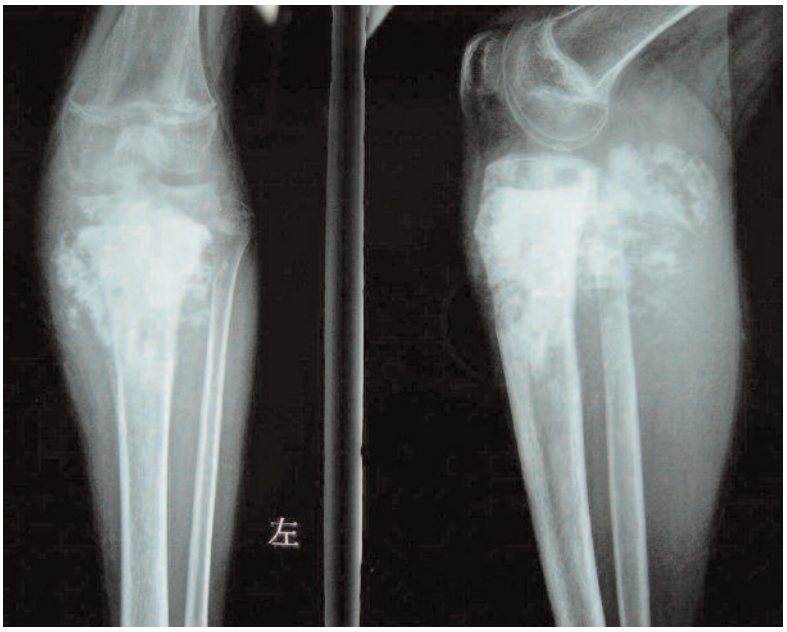

Figure 18. X-ray examination before operation.

face of the artificial semi-knee joint to the out face of the subchondral bone of allograft bone and outer face of the articular cartilage of the patient deserves great attention. Thus, the abrasion exerted on the cartilage at the opposite side would be eliminated, and the semi-replacement of the artificial joint be facilitated.

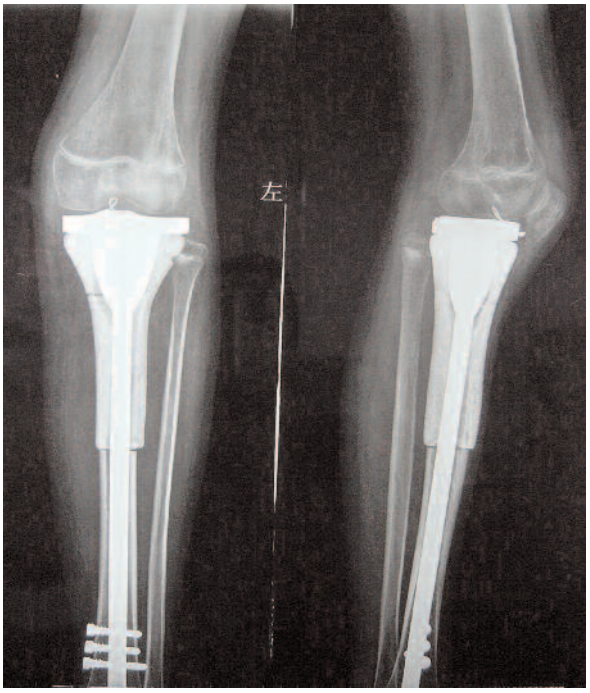

Figure 19. X-ray examination after operation.

Simultaneously, the fixation equipments, such as intramedullary pin, etc, were designed depending on the characteristics of the specific patient, to achieve the combined transplantation with allograft bone. The design of the artificial semi-joint prosthesis can be handled freely according to the clinical requirements. One of the unique advantages of the custom-made joint prosthesis is that surgeons can take part in the design process, reflecting the surgery protocol and specific desires through the design. After 18 months of follow up, no osteoarthritis was reported.

Design of the Intramedullary Pin

The keyhole intramedullary pin with the transverse section in the shape of clover had three longitudinal gabs (recesses) throughout the whole lengthways, so the effective space in the medullary cavity was increased within the working length, which afforded conditions for vascularization reconstruction, and the contacting surface between intramedullary pin and the internal surface of the medullary canal was reduced, which degraded the osteonecrosis and accelerated the revascularization of the allograft bone and autogenous bone. After the removal of the tumor from right inferior tibia segment, the bone defect was reconstructed by combined transplantation of artificial tibia condyle joint prosthesis and APC based on the rapid prototyping technique. The right femur

was found obviously thickened. Both orthotopic and lateral position X-ray films demonstrated newly formed bone along the intramedullary pin, named "endogenous callus surrounding the intramedullary pin". The newly formed bone density was even, and in an increasing tendency. Autobone became thickened. New medullary canals were shaped between original cortical bone and the newly formed bone. The newly formed bone crossed the epiphysis space and fused with the allograft bone, indicating a novel bone healing way. The enlargement of the space in intramedullary cavity and the reduction of contact surface between the intramedullary pin and the solid bone offered the favorite environment leading to reconstruction of blood circulation, which played significant roles in bone healing.

Design and Manufacture of the Synthetic Bone

Bioactive bone is degraded gradually through metabolic activities and replaced by newly formed autobone. The key point was to facilitate penetration of bioactive materials (growth factor, bone cells) and extracellular liquid inside the synthetic bone. It was reported that the pore radius of the porous bone substitute over 10 μm allowed the ingrowth of bone cells, 10-50 μm[4,5]. Regarding the necessity of bioactive material penetration and ingrowth of blood vessels inside the structures, the pore radius of the three-dimensional microtubule structures was designed over 250 μm by Unigraphics, and the inter-pores distance was in range of 1800-2000 μm, to secure the access of the microtubule circulation. As for the micropore circulation, we used the porous tricalcium phosphate, which formed the porous structure after gasification and baking at high temperature, with porosity of 100%. There were 1-10 interconnections between the spherical pores. The study showed that the customized synthetic bone possessed a mean microtubule size of 220-250 μm, a mean pore size of 250-300 μm and a mean interconnection size of 50-100 μm. Thus they favored bone calcification and double circulations efficiency inside the porous material. The structure facilitated the penetration of bioactive components (growth factor, bone cells) and tissue liquid inside the synthetic bone, minimized the time of blood vessel ingrowth, and eventually accomplished the cell proliferation and penetration and resorption of bone substitute.

Surgery Protocol

Canadell et al[6] firstly reported the lib salvage surgery with epiphyseal preservation. After finishing courses of preoperative chemotherapy, they resected the tumor and preserved the epiphysis, the repaired the defect with allograft bone. Enlightened by the protocol, we used half joint replacement and preserved the epiphysis at the opposite side. In the study of Manfrini et al[7], 6 patients with osteosarcoma in proximal tibia were available for the final evaluation. From the date of surgery to the end of skeletal growth, patient height had an average increase of 22 cm, and the average limb length discrepancy was 2.2 (0.5-3.3) cm, which could be clinical negligible and unnecessary for further surgical rectification. Functional results averaged 95% compared with normal functional limbs. No patient reported having knee instability or anterior cruciate ligament laxity. In this study, the limb length discrepancy was 38.33 mm. The joint had satisfactory stability, with no sideway translocation. No obvious complication was observed. And epiphysis healing was ideal.

The design and manufacture of the artificial semi-knee joint based on CAD relieved the necrosis and poor matching of the joint surface following allograft bone transplantation, preserved the healthy epiphysis of the affected limb and minimized the effect of the surgery on the limb length discrepancy. Thus, it has the bright future, but crucial attention should be paid to improving the fitting satisfaction. To ensure the smooth performance of the surgery and the customization of the prosthesis, the design should be based on close collaboration between the technician and the surgeon.

Acknowledgements

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Conflict of Interest

The Authors declare that they have no conflict of interests.

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