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Application Of 3D Printing Customized Bone Cement Molds In Reconstructing The Defect Of The Proximal Humerus And Distal Radius After Oncologic Resection: A Case Series Report

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Abstract

Background: Reconstructing the defect of the proximal humerus and distal radius after en bloc resection of tumors is challenging for surgeons. We present a defect reconstruction technique using bone cement prosthesis shaped by 3D printing customized molds in a case series as well as the oncologic and functional outcomes of these cases.

Methods: A total of thirteen bone tumor cases (eight cases in the proximal humerus and five cases in the distal radius) of patients who experienced this reconstructive method from 2014-2019 were retrospectively reviewed. Local recurrence, metastases, complications, musculoskeletal tumor society score (MSTS score), and visual analogue scale (VAS) were used to evaluate the outcomes.

Results: The average follow-up period was 46.5 months (range, 27-76 months). At the end of the follow-up, neither metastasis nor recurrence was found in all cases, and no patients demonstrated complications of fracture, infection, or implant loosening (only one patient who underwent proximal humerus resection and reconstruction complained of weakness in lifting the arms). The average MSTS score was 23.2 (77.2%, range, 66.7%-80%), and the average postoperative VAS was 1.31 ± 0.48 (range, 1-2).

Conclusion: Bone cement prosthesis molded by 3D printing can be an effective and inexpensive option for reconstructing the proximal humerus and distal radius after en bloc resection of bone tumors. We recommend this method especially for elderly patients who need to undergo this procedure and do not require much function of the upper extremity.

Level of evidence [illegible], a retrospective study.

Background

Primary bone tumors typically originate in the metaphysis of long bones, and in the upper extremity, the proximal humerus and distal radius are its frequently breeding sites (1). The proximal humerus is the most common site of osteosarcoma in upper limb (2). while the distal radius is the third most involved site of the giant cell tumor (GCT) following the distal femur and proximal tibia (3). Surgical treatment can be the only choice for most bone tumors, which mainly include intralesional curettage, en bloc resection, or amputation (4). However, with the improvement of imaging technology, which allows better surgical planning and delicate tumor resection, and with the application of neoadjuvant chemotherapy to decrease local recurrence, more and more malignant or aggressive bone tumors can be treated by limb salvage surgery instead of amputation (5). Currently, for oncologic surgical treatment, en bloc resection has become the optimal surgical option for aggressive or even malignant bone tumors (6, 7). However, to achieve a lower local recurrence, extensive tumor resection is usually needed, which makes reconstruction after tumor resection challenging.

Reconstruction alternatives after en bloc resection include endoprosthetic replacement, osteoarticular allografts, and composites of the two (8). However, no consensus has been reached regarding the optimal reconstruction option (9). Osteoarticular allograft is a biological reconstruction option, which is an ideal method for reconstructing bone defects provided that it offers the best anatomical match. However, the supply of allograft bone restricts its application (10), and it involves possible complications such as: rejection reaction, nonunion, and possible disease transmission (11). Endoprosthetic replacement is also a feasible reconstruction method, especially for large bone defects with comparably favorable functional outcomes (12). Major complications of endoprosthetic replacement include subluxation, aseptic loosening, and instability, which commonly lead to implant revision or removal (13). Moreover, the risk of postoperative infection resulted from endoprosthetic replacement can be relatively high, which was reported to be approximately 10% by Racano et al (14). Since the price of the prosthesis is very high, patients may not be able to afford the remedy treatment once the surgery fails.

This research aimed to introduce an novel method for reconstructing bone defects in the upper extremities after oncologic en bloc resection: A bone cement prosthesis (or cement spacer), shaped with a mold that is produced by 3D printing technology based on the CT data of the contralateral side, was used to reconstruct the affected side in the proximal humerus or distal radius. In this study, we also reported the oncologic and functional outcomes of 13 patients who underwent this procedure.

Materials And Methods

Based on a retrospective search of our hospital records from January 2014 to December 2019, we found that a total of 13 patients diagnosed with primary malignant or local aggressive bone tumor lesions were treated with en bloc resection and reconstructed by bone cement prosthesis, nine men and four women, with an average age of 50.2 years (range, 17–70 years) at the time of surgery. All patients underwent radiography, CT, and MRI preoperatively. Plain radiographs or CT scans of the chest were required to rule out pulmonary metastasis. A needle biopsy specimen was obtained preoperatively to make a correct diagnosis for each patient. Pathological classifications of the above patients were as follows: 6 patients were diagnosed with osteosarcoma in the proximal humerus, 1 was diagnosed with invasive chondroblastoma in the proximal humerus, 1 was diagnosed with recurrent GCT in the proximal humerus, 4 were diagnosed with recurrent GCT in the distal radius, and 1 was diagnosed with recurrent aneurysmal bone cyst in the distal radius. All cases in this series were staged according to the Enneking System for Staging Benign and Malignant Musculoskeletal Tumors(15). The cases of GCT were further staged according to the Campanacci staging system(3) (Table 1).Patients with osteosarcoma received neoadjuvant chemotherapy preoperatively. This research has been approved by the IRB of the authors' affiliated institutions. All patients were informed and consent with the risks and benefits of this reconstruction method.

Table 1
Clinical data of all patients

Cases	Gender	Age(years)	Location	Diagnosis	Staging	Length of resected bone (cm)
1	Male	17	Proximal humerus	Osteosarcoma	□A	13.5
2	Male	19	Proximal humerus	Invasive Chondroblastoma	□A	13.0
3	Male	56	Proximal humerus	Osteosarcoma	□A	12.5
4	Male	61	Proximal humerus	Osteosarcoma	□A	11.0
5	Male	50	Proximal humerus	Recurrent GCT	Aggressive (Campanacci grade □)	14.0
6	Male	45	Proximal humerus	Osteosarcoma	□A	14.5
7	Male	67	Proximal humerus	Osteosarcoma	□A	9.0
8	Male	70	Proximal humerus	Osteosarcoma	□A	14.0
9	Male	42	Distal radius	Recurrent GCT	Aggressive (Campanacci grade □)	6.5
10	Female	60	Distal radius	Recurrent GCT	Aggressive (Campanacci grade □)	6.0
11	Female	55	Distal radius	Recurrent GCT	Aggressive (Campanacci grade □)	8.0
12	Female	53	Distal radius	Recurrent GCT	Aggressive (Campanacci grade □)	7.0
13	Female	57	Distal radius	Recurrent Aneurysmal bone cyst	Aggressive	7.0

Table 2
Functional outcomes

Cases	MSTS score		VAS score		Metastasis	Recurrence	Oncologic outcomes	Follow up (months)
	Score	Percentage (%)	Preoperative	Postoperative				
1	22	73.3%	8	1	None	None	CDF	64
2	20	66.7%	7	1	None	None	CDF	38
3	21	70.0%	9	2	None	None	CDF	51
4	24	80.0%	7	1	None	None	CDF	38
5	24	80.0%	8	1	None	None	CDF	15
6	21	70.0%	7	2	None	None	CDF	30
7	24	80.0%	6	1	None	None	CDF	24
8	22	73.3%	6	1	None	None	CDF	33
9	23	76.7%	7	1	None	None	CDF	39
10	25	83.3%	5	2	None	None	CDF	22
11	24	80.0%	5	1	None	None	CDF	24
12	26	86.7%	7	1	None	None	CDF	35
13	25	83.3%	6	2	None	None	CDF	36

Oncologic outcomes: CDF (complete disease free)

MSTS score is calculated as percentage of the maximum possible score of 30.

We detail this procedure in a case of reconstructing the bone defect in the proximal humerus. (The procedure for reconstructing the bone defect in the distal radius was similar to that): A 50-year-old man had a local recurrence of GCT at the right proximal humerus, who underwent intralesional curettage at the local site and had a defect filled with a bone cement spacer one year ago (Fig. 2a). As the bone cortex and marrow cavity in the proximal humerus had been damaged and their data could not be used to design the mold, we based on the CT scan data mirrored from the left humerus to complete the design. The details are presented as follows (Fig. 1):

The CT scan data of the left humerus in DICOM 3.0 format was imported into the software of Mimics 17.0 (Materialise company, Belgium) to reconstruct the model of the humerus. Mirror the image of the normal (left) humerus to the right side. Geomagic Studio(Raindrop, USA) and Materialise 3-MATIC 12.0 (Materialise, Belgium) were applied to complete the virtual repair of the humerus bone model by filling holes and redrawing mesh to make the image smooth. The distance between the apex of the humeral head and the expected osteotomy plane on the affected side was measured. The osteotomy plane was designed with a 2 cm safe surgical margin, and the length of the resected segment was 14 cm. The virtually repaired humeral bone model in STL format was imported into the Geomagic Studio software for surface reconstruction and then saved in IGES format. The SoildWorks2014 software (Dassault Systemes, France) was used to complete the mold design. The mold was designed detachable in order to make the bone cement easy to take out (Fig. 2. b1). The final mold design was imported into the industrial-grade 3D printer (3D-AZSL500, ZRapid Tech, China) to conduct printing.

All surgeries were performed by an experienced musculoskeletal oncologist (corresponding author).

Section 1: The resection and reconstruction of the proximal humerus.

Following general anesthesia, the patient was positioned in a “beach-chair” position. An incision was made from the acromioclavicular joint along the deltopectoral groove and the lateral border of the biceps muscle to an appropriate level in the arm. The cephalic vein was bluntly dissected and protected by a Pancoast's drain, then the deltoid muscle and the pectoralis major muscle were separated and retracted bilaterally. After separating the pectoralis major from its insertion into the proximal humerus, good exposure of the proximal humerus were acquired. A needle was inserted into the cortex of the proximal humerus to mark the osteotomy plane. The osteotomy plane should be at a minimal 2.0 cm from the lower boundary of the tumor lesion to ensure a wide margin, and this procedure was confirmed by intraoperative fluoroscopy. Then, the en block resection was performed with a Gigli saw at the intended osteotomy plane. The mean length of the resected proximal humerus was 12.7 cm (range, 9.0 cm to14.5 cm) in this case series. Tissues obtained from the distal medullary canal were sent for intraoperative frozen section analysis to confirm adequate margins. According to the Enneking System for Staging Benign and Malignant Musculoskeletal Tumors, no stage of proximal humeral bone tumors in these series exceeded ▯A. A wide resection was preferable, excessive resection of the adjacent soft tissue seemed unnecessary, and the rotator cuff was preserved.

Meantime, one assistant prepared the bone cement prosthesis on another operating table. The inside surface of the bone cement mold was evenly coated with a thin layer of bone wax, which made it easier to remove the bone cement prosthesis after hardening (Fig. 2. b2). After the bone cement was poured into the mold and before it self-setting, 2 shaped Kirschner wires were inserted right in the middle of the bone cement (Fig. 2. b3). The Kirschner wires supported as scaffolds, connecting the proximal bone cement to the medullary canal of the distal humerus. Curling the distal part of the Kirschner wires could improve the anti-movement stability of the bone cement prosthesis and prevent them from prolapse. The overall length of the bone cement prosthesis in this case was 270 mm, and the distance between the apex of the humerus head and the expected osteotomy plane was 140mm as preoperatively designed (Fig. 2. c). Low-viscosity cement was injected into the medullary canal of the distal humerus, and then the stem of the bone cement prosthesis was inserted and adjusted to a proper position (Fig. 2. d). After the bone cement hardened, a final fluoroscopy was conducted to confirm the implant position. The rotator cuff and capsule were repaired as much as possible. Finally, we closed the wound and immobilized the shoulder in an abduction humeral splint.

Section 2: The resection and reconstruction of distal radius

A 57-year-old woman who was diagnosed with an aneurysmal bone cyst at her left distal radius in 2019 underwent intralesional curettage followed by cancellous allografts. The patient had a local recurrence one year later (Fig. 3. a-b). She chose the option of a bone cement prosthesis to reconstruct the defect after resecting the bone tumor.

The details of the operation were as follows:

A dorsal approach was used to expose the distal radius. The extensor retinaculum was divided, and a spacing interval between the third and fourth extensor tendons was developed to enable full exposure of the distal radius. A Gigli saw was used to perform en bloc resection of the distal radius, and the osteotomy plane was at a distance of minimal 2.0 cm from the proximal boundary of the tumor lesion (Fig. 3. c). The mean length of the resected segment of the distal radius was 6.9 cm (range, 6.0 cm to 8.0 cm) in this case series. The fabrication of the bone cement prosthesis and the reconstruction procedure were similar to those used in the reconstruction of the proximal humerus described above (Fig. 3. d-f). Lastly, the dorsal retinaculum was repaired as much as possible.

No significant complications occurred during the intraoperative or immediate postoperative periods. The surgical positions of the patients were required for fixation by plaster for 4–6 weeks. Continuous passive movements started once the plaster was removed. We suggested active rehabilitation exercises but did not recommend full weight-bearing. Patients with high-grade osteosarcoma received adjuvant chemotherapy routinely after the wound had healed.

Patients were followed up every 3 months during the first year and every 6 months thereafter, during which, physical examination, VAS assessment, and X-ray scanning were performed. To rule out pulmonary metastases, a CT scan of the chest was performed every six months in the first year and every year thereafter. The functional outcomes of the reconstructed limb were assessed by a physical therapist based on the Musculoskeletal Tumor Society score (MSTS score) (15).

All statistical analyses were performed by SPSS 22.0 Statistical Package for the Social Sciences (SPSS, Inc., Chicago, IL, USA), and a p-value of less than 0.5 was accepted statistically significant. The data are presented as the mean ± standard deviation. Statistical differences in pre-and post-surgery VAS scores were compared using the paired-sample t-test.

Results

All 13 patients underwent en bloc resection of the bone tumor and reconstruction of bone defects with bone cement prosthesis molded by 3D printing. The average follow-up period was 46.5 months (range, 27–76 months). No patients demonstrated complications of nerve injury, vascular injury, fracture, infection, or bone cement implantation syndrome. No local recurrence or metastases of bone tumors were observed in these patients. All bone cement prostheses were intact at the last follow-up. The average MSTS score was 23.2 (77.2%, range, 66.7%-80%), and the average postoperative VAS was 1.31 ± 0.48 (range, 1–2), which was significantly lower than that before surgery (average preoperative VAS score was 6.77 ± 0.32 (range, 5–9)) ($p < 0.001$, and the p values were derived from two-tailed tests) (Table.2). However, one patient complained of difficulties in lifting the right arms (Fig. 4), and an X-ray showed slight subluxation of the right shoulder joint (Fig. 2e).

Discussion

It is well known that bone cement is a biomaterial with self-coagulation properties and is first used to reinforce the fixation of the femoral and acetabular components in total hip replacement (16). Owing to its excellent biocompatibility, low cost, plasticity, and strong hardness, it has been widely used in orthopedic surgery (17). Bone cement is also used as a spacer to fill the cavity left by the curetting procedure. It has the advantages of providing immediate stability and facilitating easy detection of local recurrence of tumors (18). Bone cement also plays an important role in reconstructive surgery, especially in limb salvage surgery for malignant bone tumors.

In this study, we proposed a novel method for bone defects reconstruction by using the bone cement prostheses: A handcrafted bone cement prosthesis with metal rods is used to replace the removed bone segment, during which the metal rods are also inserted into the medulla of the residual bone segment and fixed by bone cement. Since the upper extremities do not have to bear as much weight as the lower extremities, bone cement prosthesis is strong enough to perform some daily functions of the upper extremities, such as writing, combing hair, etc. To our knowledge, this method has been reported by only a few authors (19, 20) with satisfactory outcomes in the upper extremities.

However, the bone cement prostheses reported in the literature were mostly fabricated manually during surgery. As is known to all, kneading the bone cement to an epiphyseal shape is not only time-consuming but also leads to inaccuracy. The average setting time of bone cement reported by Ross et al. (21) was 13.08 mins, with a range of 7–19 mins. Due to the limited time frame in the process of surgery, it is difficult to form a suitable epiphyseal shape by manual molding in a short time, and the mismatching of the manual bone cement prosthesis after curing often requires secondary modification, thus delaying the process of surgery. Moreover, the prosthesis of a strange shape and mismatching shape will accelerate joint degeneration, cause the failure of medullary cavity support, and even easily cause the fracture of bone cement prosthesis.

We have improved the procedure on this basis: the CT data of the contralateral intact upper limbs were mirrored to the affected side according to the symmetry of the human body, based on the data, a mold was fabricated using 3D printing technology, and used to shape the bone cement prosthesis, which made the bone cement prosthesis much easier to shape and more suitable to the articular surface.

We present a case series of 13 patients with bone tumors who were treated with this reconstruction method. All patients were alive without evidence of oncologic recurrence at the last follow-up. The average MSTS score was 23.2 (77.2%, range, 66.7%-80%), which was comparable with the MSTS scores ranging from 40–80%, as reported by other authors (22–24). The functional outcomes of this method were equivalent to those of osteoarticular allografts and endoprosthetic replacement. We surmised that the anatomically precise design increases prosthesis-joint compatibility and improves patient comfort. However, one patient showed poor abductor function of the right shoulder during the one-year period after surgery. The reason might be that since the length of the resected segment of that patient was 14cm, theoretically, the more aggressive the resections had been the poorer functional outcomes would be.

Nevertheless, this study has some limitations. Firstly, the major disadvantage of this method is the nonunion of the bone-to-cement interface. Although the strength of the bone cement is strong enough to undertake daily activities, it will not be able to reach the osseous fusion at any time. Secondly, the evidence grade of this study is low because the number of enrolled patients is small. Hence, further verification of the outcomes of this method with a large-scale, and randomized study will be required. Third, a longer follow-up period is required to observe some other complications, such as, fracture of the bone cement prosthesis, and implant dislocation, which did not occur in this series.

Conclusions

A novel and innovative method of reconstructing defects with bone cement prosthesis molded by 3D printing after en bloc resection of bone tumors in the upper extremity is proposed and detailed. Also good outcomes of this case series in the short and medium term are presented. We recommend that this method be considered as an option for reconstructing the defect after en bloc resection of tumors in the upper limbs.

Declarations

Ethics approval and consent to participate, Consent for publication

This research has been approved by the IRB of the authors' affiliated institutions.

The patients and/or their families were informed that data from the case would be submitted for publication, and gave their consent.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors have declared that no competing interests exist.

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Authors' contributions

MW conceived and designed the study, who together with CW and LLZ designed the 3D printing mold. MW performed the surgery, TFR were assistant. YQH completed the follow-up work. SK wrote the main manuscript. MW edited the manuscript. All authors read approved the final version of the manuscript.

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Figures

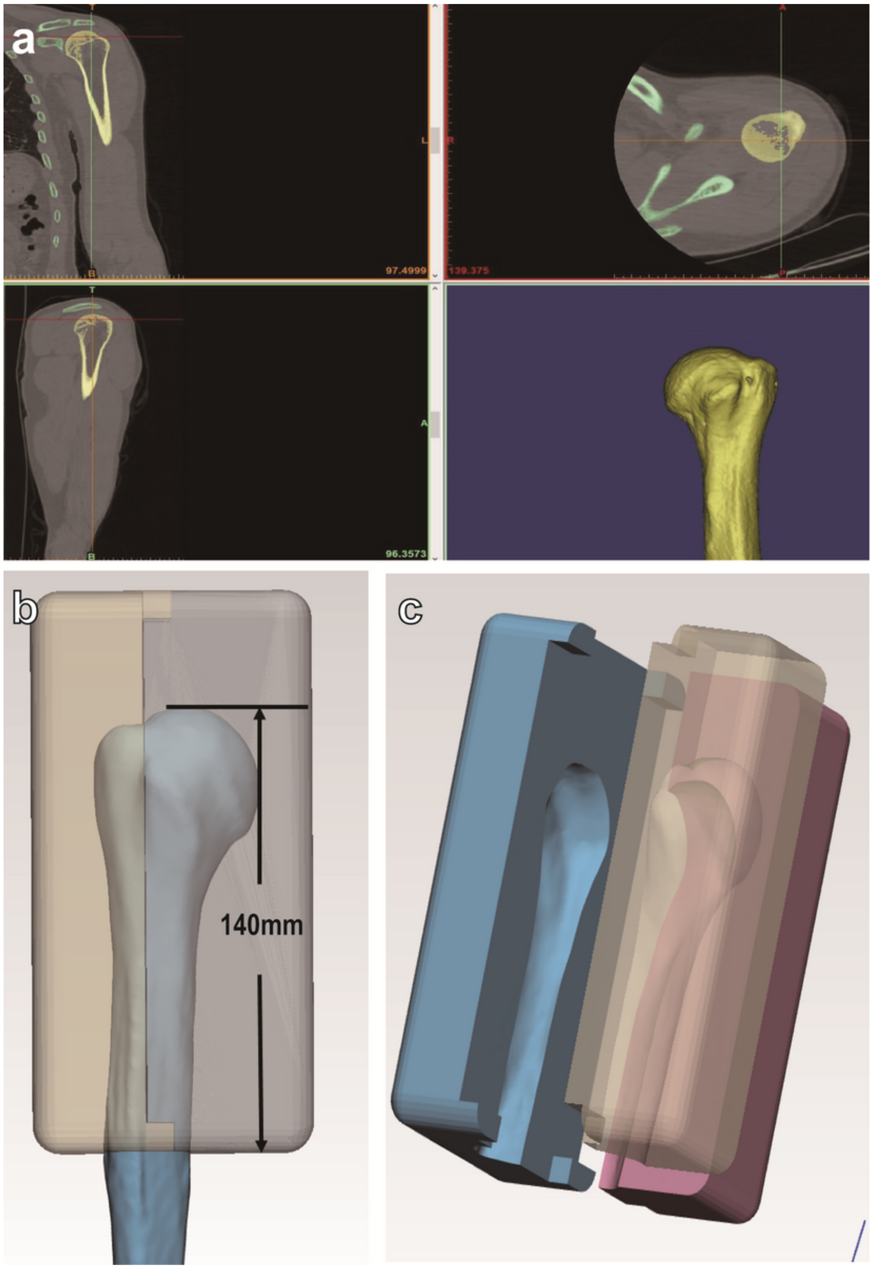

Figure 1

The mold used for reconstructing the defect after resection of the bone tumor was designed based on the CT scan data of the left humerus before the surgery. (a). The CT scan data of the left humerus was imported into the software of Mimics 17.0 to reconstruct the model of humerus. (b). The distance between the apex of the humerus head and the expected osteotomy plane was 140mm as the preoperative design. (c). The mold was designed detachable to make the bone cement easy to take out.

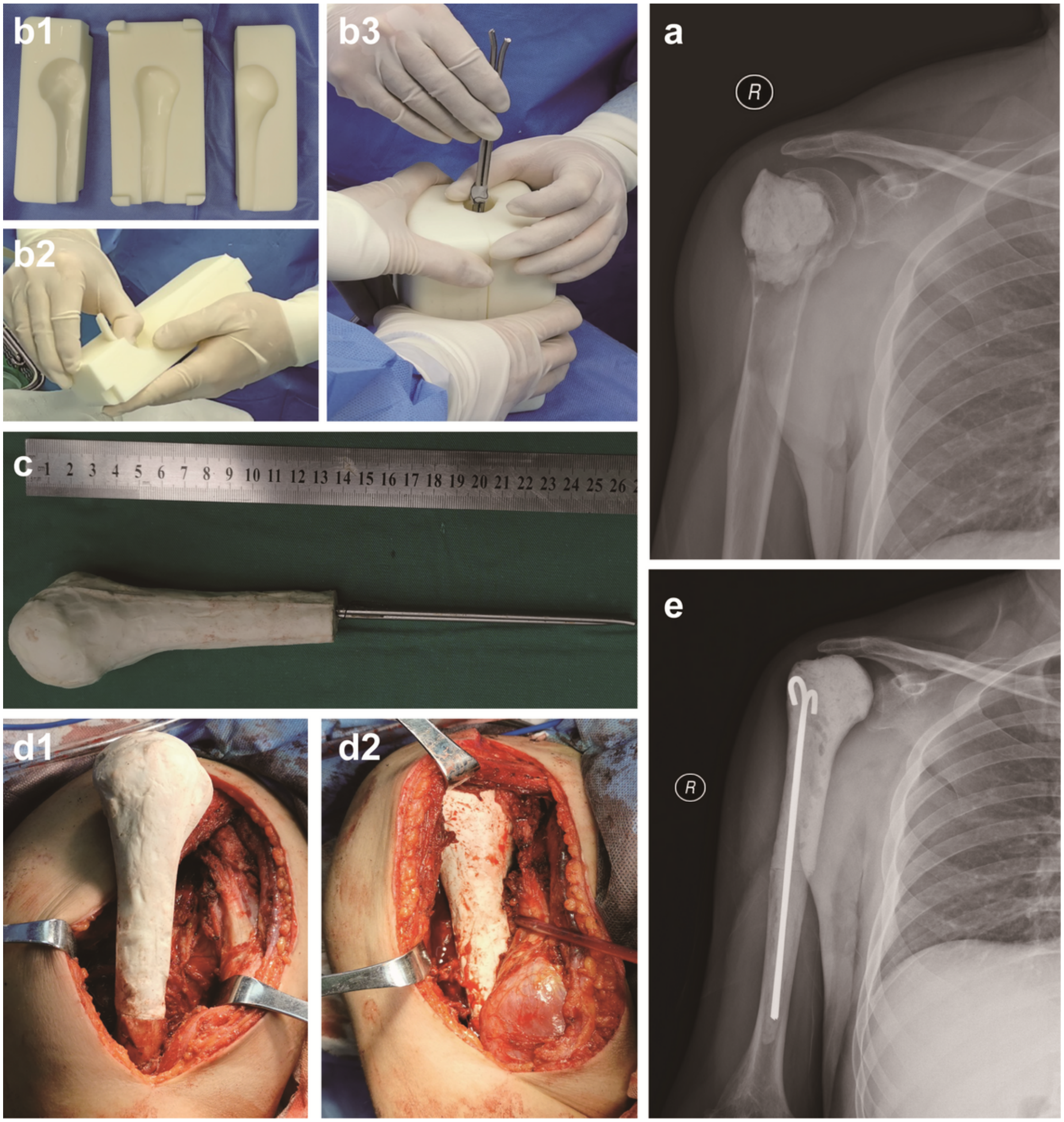

Figure 2

A 50-year-old man who had a local recurrence of giant cell tumor at right proximal humerus underwent reconstructive surgery with bone cement prosthesis molded by 3D printing technology. (a). Anteroposterior radiography of a 50-year-old man who had a local recurrence of giant cell tumor at proximal humerus which was filled with bone cement after intralesional curettage 1 year ago. (b). The fabrication of the bone cement prosthesis (b1. Each module of the cement-spacer shaping mold; b2. The internal surface of the mold was evenly coated with a thin layer of bone wax; b3. Two shaped Kirschner wires were inserted right in the middle of the bone cement). (c). The molding of bone cement prosthesis. (d). The bone cement prosthesis fits the defect perfectly. (e). Postoperative anteroposterior radiography of the right shoulder.

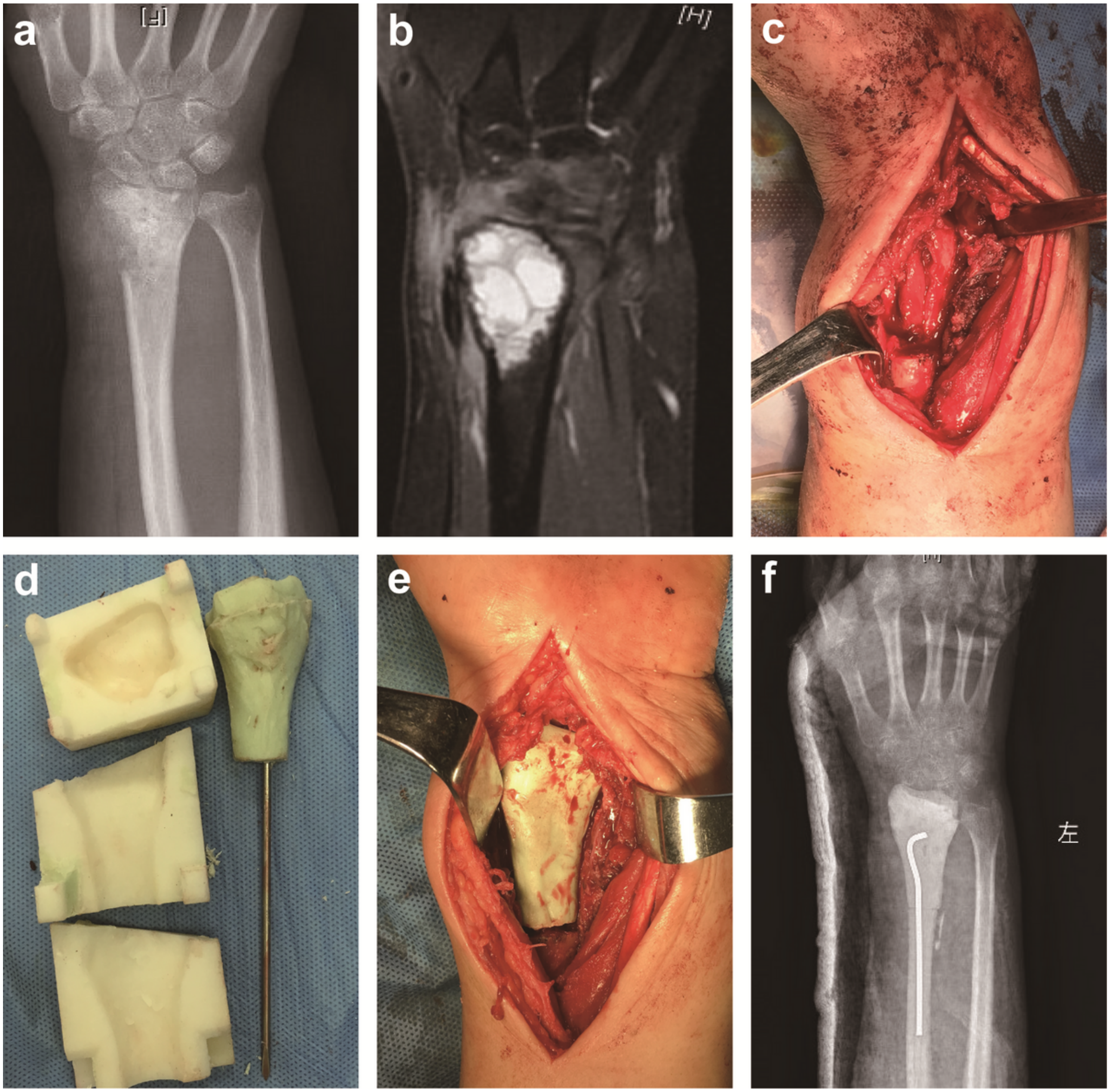

Figure 3

A 57-year-old woman who had a local recurrence of aneurysmal bone cyst at left distal radius underwent reconstructive surgery with bone cement prosthesis molded by 3D printing technology. (a). Anteroposterior radiography of 57-year-old woman with aneurysmal bone cyst of the distal radius. (b). MRI showed the extent of the tumor and soft tissue mass. (c). The distal radius with the tumor was removed through the dorsal approach. (d). The shaped bone cement prosthesis. (e). The bone cement prosthesis fits the defect perfectly. (f). Postoperative anteroposterior radiography of the left wrist.

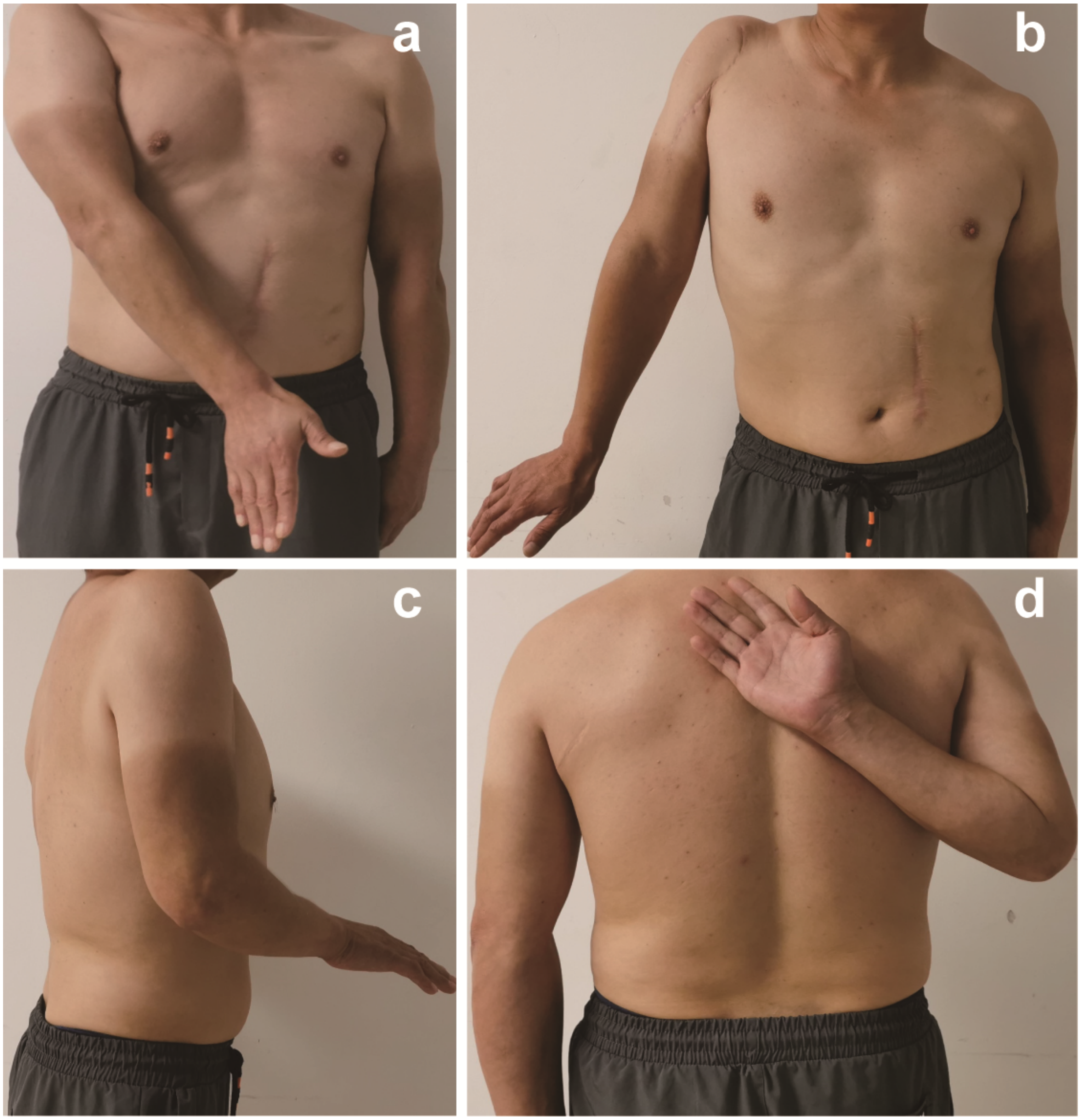

Figure 4

Functional outcomes of the patients' right upper limb at the ninth month after surgery. (a). The patient showed a good abduction function of his right shoulder. (b). The patient had a mild limit on the abduction of the right shoulder joint mainly caused by the weakness of the deltoid. (c). Also, a mild limit on the external rotation movement. (d). The patient showed an excellent internal rotation movement.