3D Printing in Medicine

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Treatment of distal radius giant cell tumor with 3D-printed metal prosthesis combined with mesh patch

Tianwen Zhang[1], Xiaoning Tan[1], Zhenchao Yuan[2*], Bin Liu[2*] and Jiachang Tan[2*]

Abstract

Objective This study introduces a surgical technique involving the use of 3D-printed all-metal prostheses combined with mesh patches for the treatment of distal radial giant cell tumors, analyzing and evaluating the midterm outcomes for patients undergoing this treatment. The experience provides insights into the application of prosthesis replacement for reconstructing distal radial defects.

Methods From January 2018 to January 2021, our center treated five cases of distal radial giant cell tumors using 3D-printed all-metal prostheses combined with mesh patches. Postoperative pain, range of motion, and grip strength were evaluated for all patients. Oncological outcomes, complications, and degenerative changes in the wrist joint were also assessed. Functional outcomes were evaluated based on the Mayo wrist score system.

Results The average follow-up period was 40.8 months (range: 32-66months). At the last follow-up, the mean range of motion (ROM) in the affected wrists was 20° extension, 21.6° flexion, 71.2° pronation, and 50° supination. The mean grip strength on the affected side was 64.2% compared to the unaffected side, with a Mayo score of 70. There were no incidences of aseptic loosening, wrist subluxation, or infections post-prosthesis replacement, although two cases presented with distal radioulnar joint dislocation. Of these, one case demonstrated ulnar impaction syndrome with positive ulnar variance and lunate bone degenerative changes on the 12-month postoperative radiographs. No recurrences or metastases were observed.

Conclusion Utilizing 3D-printed metal prostheses and mesh grafts for the treatment of Campanacci Grade III or recurrent giant cell tumors of the distal radius is an effective approach. This strategy provides favorable functional outcomes during the early to mid stages of treatment, while also maintaining a low risk of complications. The concurrent use of mesh grafts facilitates early postoperative exercise, thereby accelerating functional recovery. Moreover, the intraoperative protection or reconstruction of joint ligaments, along with precise matching of the prostheses, contributes to a reduction in the risk of complications.

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Background

Giant Cell Tumor (GCT) of bone is a locally aggressive lesion, accounting for 5% of primary bone tumors [1]. The distal radius is the third most common site for the occurrence of GCTs. For patients with Campanacci Grade III or recurrent distal radial GCTs [2], en bloc resection is the standard treatment approach. However, due to the high functional demands of the wrist joint, reconstructing the distal radial defect presents a challenge. Current reconstruction techniques include arthrodesis [3], vascularized and non-vascularized autologous fibula grafting [4], ulnar transposition [5], and prosthetic reconstruction [6], each with its unique advantages and limitations. Yet, the gold standard for reconstructing the distal radial wrist joint has not been established.

With the advancement of 3D printing technology, prosthetic materials, and their designs, wrist joint prosthesis replacement has emerged as an option for patients with distal radial giant cell tumors. Over the past three decades, several different wrist prosthesis replacement surgeries have been reported, achieving reasonable outcomes but also reporting common complications such as radiocarpal dislocation, distal radioulnar joint dislocation, poor matching between the internal prosthesis and wrist bones, and aseptic loosening [7]. These limitations have restricted their clinical application. Optimizing prosthetic design and improving surgical techniques to enhance postoperative wrist joint function and reduce complications remain areas of focus.

This study retrospectively analyzes five cases of distal radial giant cell tumors treated at our center from January 2018 to January 2021 with 3D-printed metal prostheses combined with mesh patches. It evaluates the clinical efficacy, elaborates on the prosthetic design and surgical philosophy, and proposes methods to reduce postoperative complications and improve mobility after prosthetic replacement surgery. This provides experience for the application of prosthesis replacement in reconstructing distal radial defects.

Materials and methods

Patient data

Between January 2018 and January 2021, five patients with distal radial giant cell tumors underwent tumor en bloc resection followed by reconstruction with 3D-printed metal prostheses combined with mesh patches at our institution. Inclusion criteria were as follows: (1) patients with a pathological biopsy-confirmed diagnosis of giant cell tumor of the distal radius (Campanacci grade III or local recurrence) without distant metastasis; (2) patients who underwent 3D-printed metal prosthesis reconstruction combined with mesh grafting at our hospital. Exclusion criteria were: (1) patients with other severe diseases or those who were unable to tolerate surgery based on a comprehensive evaluation; (2) joint infection; (3) patients unable to perform postoperative functional exercises as prescribed; (4) patients with incomplete follow-up data. Among these patients, three were male, and two were female. The average age at admission was 29 years (range: 22–37 years). All patients were confirmed to have giant cell tumors by pathological biopsy and underwent comprehensive preoperative assessments, including X-rays, CT with three-dimensional reconstruction, and MRI scans. Follow-ups were conducted monthly for the first six months postoperatively, then every three months thereafter, and biannually after the first year. During follow-ups, patient pain, wrist joint range of motion (ROM), grip strength on the affected side, Mayo wrist scores, and complications such as prosthesis loosening, joint degeneration, and dislocation were evaluated. Pain was assessed using the Visual Analogue Scale (VAS). ROM was recorded using a goniometer. Grip strength was measured with a hydraulic hand dynamometer. Complications were evaluated through patient symptoms, physical examination signs, and X-ray examinations.

Prosthesis design and manufacturing

The prostheses utilized in this study were designed by the clinical team at the Bone and Soft Tissue Tumor Center of the Affiliated Tumor Hospital of Guangxi Medical University. They were manufactured by Chunli Co., Ltd., located in Tongzhou, Beijing, People's Republic of China. The prosthesis is a fully integrated implant made of titanium alloy, consisting of the prosthetic stem, body, and metal articular surface base (Fig. 1). The stem, designed for insertion into the residual medullary cavity of the distal radius, features a roughened surface with slight textures and grooves to enhance the gripping strength of bone cement. Its length is adjustable based on the segment of bone resection, and it is designed to ensure sufficient length for stable implant fixation. The body of the prosthesis slightly expands to replace the osseous defect following tumor excision, with its length determined by preoperative measurement of the required bone resection site. The proximal end of the body includes a porous trabecular collar to facilitate bone bridging through grafting. The distal end of the prosthesis mirrors the anatomical structure of the healthy distal radius, and the articular contact surfaces are highly tailored based on preoperative CT three-dimensional reconstructions assessing changes in the contralateral carpal and ulnar bones. Prefabricated holes are strategically placed on the distal, ulnar, and radial surfaces of the prosthesis for optimal integration.

The mesh graft consists of a layer of finely woven polytetrafluoroethylene (PTFE) mesh and a layer of expanded PTFE. It is a material with excellent biocompatibility and a low coefficient of friction.

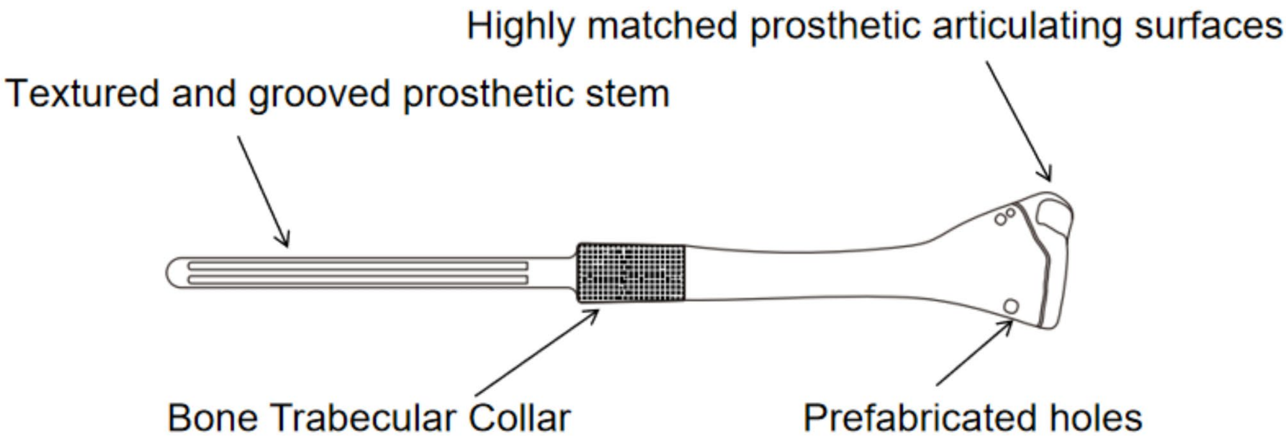

Fig. 1 Metal integrated prosthesis

Surgical technique

The patient is positioned supine, standard disinfection and draping are performed. After applying pressure with a tourniquet, a longitudinal incision is made along the ulnar side of the distal radius. The skin, subcutaneous tissue, and deep fascia are sequentially incised, entering the interval between the brachioradialis and flexor carpi radialis muscles to access the distal radius tumor. The tumor is dissected while preserving the wrist joint capsule and surrounding ligaments, ensuring adequate protection of nerves and vessels. The tumor is excised in one piece, and the proximal radius is osteotomized. Prior to implanting the prosthesis, a mesh graft is wrapped around the distal radius prosthesis and sutured to the preformed holes at the distal end of the prosthesis to secure it in place, preventing relative displacement. The medullary cavity of the radius is reamed, and the prosthesis is installed. When the surrounding joint capsule and ligaments of the wrist joint can be fully or largely preserved, non-absorbable sutures (size 2) are used to directly suture the surrounding joint capsule and ligaments to the 3D printed prosthesis wrapped with the mesh patch. Important ligaments, such as radiocarpal ligaments or the dorsal radial-ulnar ligament and palmar radial-ulnar ligament of the triangular fibrocartilage complex (TFCC), are sutured as much as possible to the pre-made holes on the prosthesis. The remaining surrounding joint capsule and other soft tissues are sutured to the mesh patch according to their anatomical positions, forming a tightly integrated soft tissue envelope. Intraoperative fluoroscopy ensures satisfactory fixation, with the proximal prosthesis stem fixed using bone cement. The incision is thoroughly irrigated, and allograft or autograft bone is implanted at the radial, palmar, and dorsal sides of the prosthesis bone trabecular collar. A drainage tube is placed, and the tissues are sutured layer by layer.

Postoperative Management

The affected limb was immobilized using a plaster cast in a position with the elbow flexed and the forearm in supination. The immobilization across the elbow joint was maintained for three weeks. On the day following the surgery, patients were instructed to perform finger exercises. Flexion and extension exercises began three weeks post-operatively, and rotational movements of the wrist commenced after six weeks. Early postoperative exercises were encouraged to achieve a more flexible range of motion (ROM). Additionally, the initiation and progression of wrist movements were tailored based on the extent of soft tissue preservation during surgery for each patient. Exercise intensity was gradually increased according to each patient's tolerance and recovery progress.

Results

In this group of 5 patients, the prostheses were designed based on preoperative CT three-dimensional reconstruction and assessment, with the main length of the prosthesis matching the length of the osteotomy during surgery. In all 5 patients, most of the radiocarpal ligaments and the wrist joint capsule were preserved, allowing for satisfactory reconstruction of the radiocarpal joint. However, due to early surgical experience and tumor invasion, the triangular fibrocartilage complex (TFCC) was only partially preserved in the first 4 patients (Patient IDs 1, 3, 4, and 5), with the remaining radial-ulnar joint ligaments being sutured and reconstructed. In the last patient (Patient ID 2), the palmar and dorsal radial-ulnar ligaments of the TFCC were fully preserved. All patients underwent postoperative plaster fixation.

The average follow-up duration for all patients was 40.8 months (range: 32–66 months). At the last follow-up, the mean range of motion (ROM) for the affected wrist joints was 20° in dorsiflexion, 21.6° in palmar flexion, 71.2° in pronation, and 50° in supination. The mean grip strength on the affected side was 64.2% compared to the unaffected side, with a Mayo score of 70. There were no incidences of aseptic loosening, partial dislocation of the wrist joint, or infections post-prosthesis replacement. However, two cases presented with distal radioulnar joint dislocation, one of which showed ulnar impaction syndrome with positive ulnar variance and degenerative changes in the lunate bone on the 12-month postoperative radiographs. Additionally, varying degrees of ulnar deviation of the wrist were observed in all 5 cases. There were no cases of recurrence, metastasis, amputation, or death. Table 1 summarizes the functional outcomes and complications. Figures 2 and 3 illustrate two typical cases.

Discussion

Campanacci Grade III or recurrent giant cell tumors of the distal radius are locally aggressive lesions with a relatively high recurrence rate. The primary treatment objectives are as follows: complete tumor excision to reduce the local recurrence rate and to maximally preserve wrist joint function [1]. Since 1957, when Gold first utilized a bone cement-type stainless steel prosthesis for treating giant cell tumors of the distal radius [8], prosthetic joint replacement surgeries for reconstructing distal radial defects have seen significant improvements and developments. Current literature reports favorable outcomes of prosthetic reconstructions, but also notes dissatisfaction with mobility and complications. Designing an ideal wrist joint prosthesis still requires more clinical research and experimentation. In this context, we have performed joint replacement surgeries using customized bone cement 3D-printed, fully integrated metallic prostheses combined with mesh grafts on five patients with Campanacci Grade III or recurrent distal radial GCTs. Compared to previous studies, satisfactory results were obtained in the short to medium term [9, 10 11, 12] (Table 2).

In previous studies, the design of distal radius prostheses has varied, each with its respective advantages and disadvantages. For example, designs incorporating a bipolar hinge have been used to improve postoperative wrist mobility [13], but these can increase the risk of loosening and dislocation. The addition of a polyethylene liner at the radiocarpal joint has been employed to reduce the occurrence of degenerative changes in the carpal bones [14], but it can also increase the risk of liner malposition or separation. Fully metallic prostheses have been designed to enhance stability [15], and pre-fabricated holes have been included to facilitate the reconstruction of soft tissues intraoperatively. Biomorphic prosthetic stems have been created to reduce postoperative loosening [9]. This study referenced the originally designed prosthesis and developed an integrated metal prosthesis. Considering the narrow and uniform medullary cavity of the radius, a bone cemented prosthesis stem was used to achieve better initial stability. Surface roughening and the addition of subtle textures and grooves were applied to the stem portion of the prosthesis to increase surface area and enhance the grip of the bone cement. The base of the prosthetic body was designed with a porous trabecular collar, around which allograft or autograft was placed intraoperatively, promoting osseointegration and external bridging to improve the long-term stability of the prosthesis and reduce the risk of loosening. Considering the wrist is a non-weight-bearing joint, to reduce the occurrence of joint dislocation, the polyethylene insert at the distal end of the prosthesis was removed. Simultaneously, a metal contact surface matching the original radius-carpal contact area was designed to minimize degenerative changes due to metal-carpal joint contact. In our study, five patients achieved good functional mobility without degenerative changes in the wrist joint due to metal contact, and no wrist dislocations were observed. During an average follow-up of 40.8 months, no signs of prosthesis loosening were detected, and in three cases, bone scab formation around the trabecular collar was observed.

Satisfactory outcomes in joint prosthesis replacement surgery are also critically dependent on the thorough reconstruction of the surrounding soft tissues. Li Min et al. designed precise pre-fabricated holes in the prosthesis,

Table 1 Patients' basic characteristics

Patient ID	Age	Tumor classification	Follow-up (month)	Arc of movement				Hand-grip strength(compared to normal side)	Myao scores	Complications
				Extension	flexion	pronation	supination			
1	22	Relapsed	32	15°	30°	60°	30°	60%	65	Distal radioulnar joint dislocation, ulnar impingement syndrome
2	29	III	31	20°	5°	90°	90°	85%	75	no
3	37	III	66	25°	28°	66°	53°	75%	70	Distal radioulnar joint dislocation
4	23	Relapsed	35	12°	8°	65°	45°	52%	65	no
5	35	III	40	28°	37°	75	32°	49%	75	no

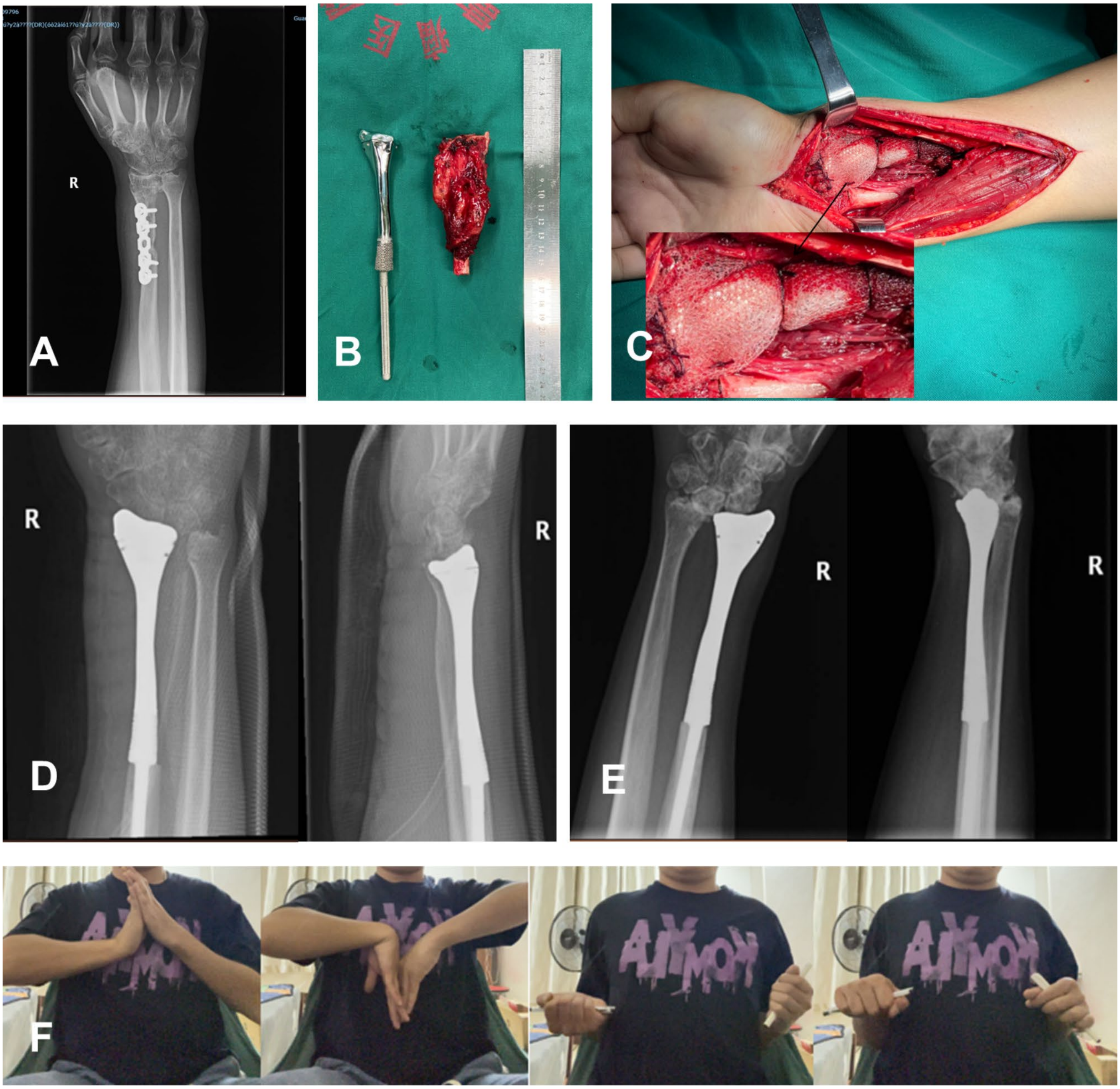

Fig. 2 Presents a case study of a 22-year-old male(Case 1), approximately 32 months post-prosthetic replacement surgery following the excision of a recurrent giant cell tumor of the distal radius (GCT). (**A**) Preoperative X-ray; (**B**) Intraoperative images of tumor excision and prosthesis: During the surgery, the radiocarpal ligaments and joint capsule of the radiocarpal joint were largely preserved, with a small portion of the radial-ulnar joint ligaments and other structures of the triangular fibrocartilage complex (TFCC) preserved and sutured to the prosthesis for reconstruction.; (**C**) Intraoperative placement of the 3D-printed metal prosthesis wrapped in a mesh graft; (**D**) Postoperative X-ray (3 days, anteroposterior and lateral views); (**E**) Postoperative X-ray (12 months, anteroposterior and lateral views): No recurrence of the tumor was observed. Mild ulnar deviation of the wrist and distal radioulnar joint dislocation were noted. The joint space of the radiocarpal joint was narrowed, with signs of disuse osteopenia in the carpal bones. Positive ulnar variance and potential ulnar impaction syndrome, along with possible avascular necrosis of the lunate, were also observed.; (**F**) Functional follow-up at 32 months post-surgery: wrist range of motion: extension: 15°; flexion: 30°; pronation: 30°; supination: 60°; grip strength: 60%; Mayo wrist score: 65 points

allowing for the specific sequence and tension of sutures needed to reconstruct the surrounding joint capsule and ligaments [9]. Pobe Luangjarmekorn et al. utilized autologous tendons to reinforce the radiocarpal and radioulnar ligaments [16]. DING Hao et al. achieved a tighter and more stable soft tissue envelopment by incorporating LARS ligaments [17]. Compared to these methods, our study also incorporates the use of a mesh graft alongside the design of pre-fabricated holes in the prosthesis, aiding in the precise suturing or reconstruction of the wrist joint and surrounding soft tissues. Mesh grafts, made from biocompatible materials, have been widely used in

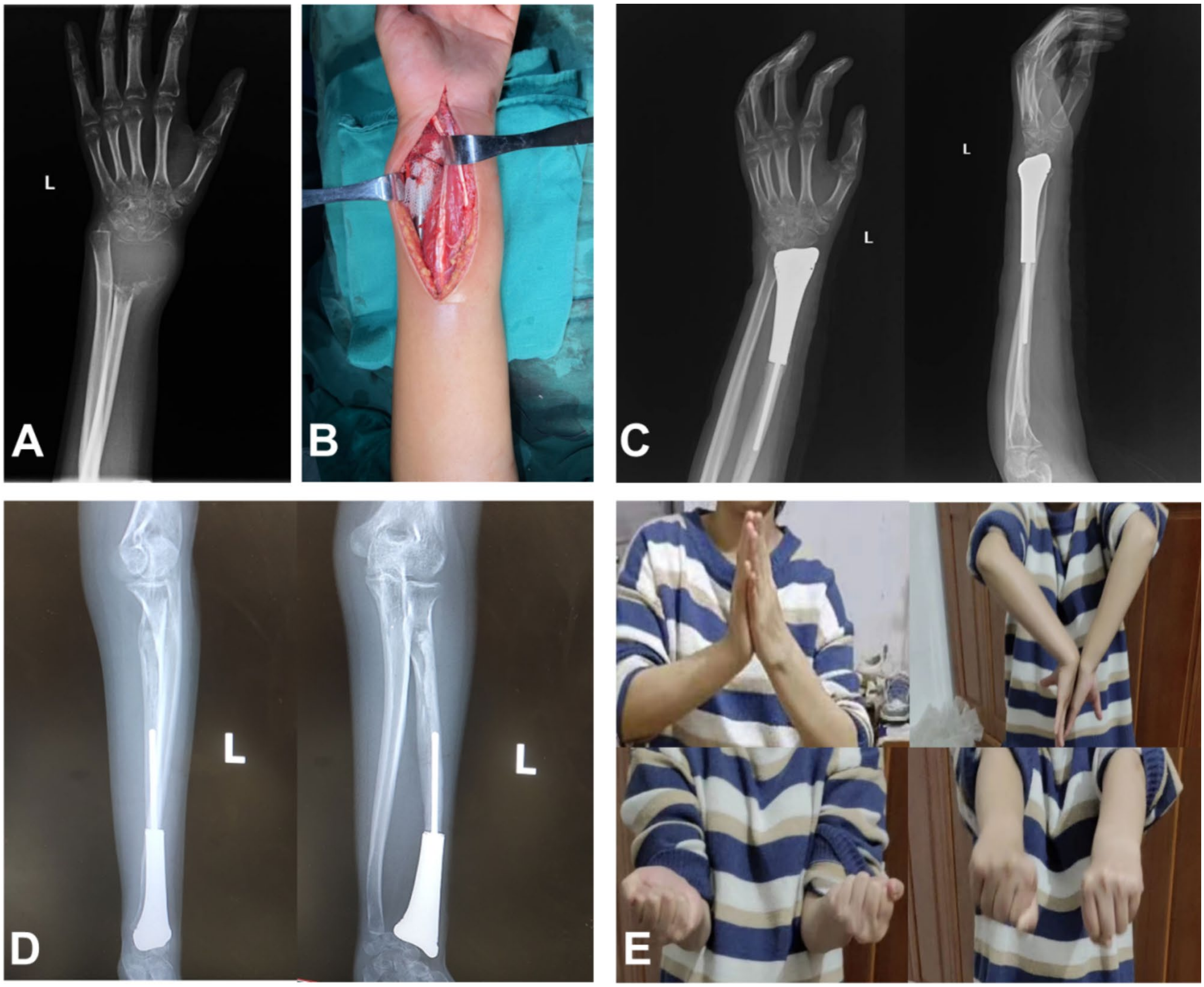

Fig. 3 Features a case study of a 25-year-old female(Case 2), 31 months post-prosthetic reconstruction following the excision of a Campanacci Grade III giant cell tumor of the distal radius (GCT). (**A**) Preoperative X-ray image; (**B**) Intraoperative implantation of the 3D metal prosthesis wrapped with a mesh patch: The radiocarpal ligaments and joint capsule of the radiocarpal joint were largely preserved, as well as the palmar and dorsal radial-ulnar ligaments and the triangular fibrocartilage complex (TFCC).; (**C**) X-ray images from the third postoperative day showing anteroposterior and lateral views; (**D**) X-ray images at 32 months postoperatively: The prosthesis is in place, with no recurrence of the tumor. Mild ulnar deviation of the wrist is observed, but no subluxation of the radiocarpal joint or distal radioulnar joint dislocation has occurred.; (**E**) Functional follow-up at 31 months post-surgery: wrist range of motion: extension: 20°; flexion: 5°; pronation: 90°; supination: 90°; grip strength: 85%; Mayo wrist score: 75 points

other types of tumor-related joint replacements. In our study, the mesh graft was tightly wrapped around the prosthesis, providing additional anchoring points for suturing critical structures such as the joint capsule and ligaments, thereby enhancing the stability and durability of the reconstructed structures. This supports early postoperative functional exercises and reduces the risk of joint stiffness. In our study, most patients demonstrated good joint stability and functional recovery post-surgery. Although one patient, due to poor compliance, did not engage timely in flexion and extension exercises and only recovered a wrist range of motion of 25°, their daily life and satisfaction were not significantly impacted (Fig. 3E).

In early follow-up, this study noted distal radioulnar joint dislocation in two patients (Fig. 2E), a common complication during wrist arthroplasty. Dislocation of the distal radioulnar joint is typically associated with the failure to preserve the triangular fibrocartilage complex (TFCC), a crucial stabilizer of the radioulnar joint [18]. This study underscores the dorsal and palmar radioulnar ligaments within the TFCC as the most critical structures. Instability of the distal radioulnar joint is usually caused by damage to these two parts of ligaments, which are also essential for wrist rotational functionality. For instance, the dorsal ligament becomes taut during pronation, and the palmar ligament tightens during supination to maintain rotational stability [19]. Therefore, on

Table 2 Previous prosthetic replacement for giant cell tumor in the distal radius

Investigator The data	Case	Material of implant	fixation technique of implant	Follow-up (month)	flexion / Extension	pronation / supination	grip strength	Function	Complications
Li Min et al. [9]	13	3D printing prosthesis	cementless	14.45	30°/61.5°	57.27°/59.95°	23.6 mmHg	DASH scores 18.7 Mayo scores 72	No
Shuai Zhang et al. [11]	11	Radial alloy prosthesis with polyethylene liner	cement	34.6	20°/30°	25°/40°		Mankin score 3 excellent case, 4 good cases, 5 passable cases and 1 poor case	No
Hatano et al. [10]	2	Ceramic	cement	168/120	15°/30° 15°/35°	45°/30° 50°/60°	22 mmHg 29 mmHg	MSTS scores 83	degenerative changes in the wrist joint, aseptic loosening.
Zhi jin Xie et al. [12]	4	Ball-and-socket design full wrist joint	cement	25.5	48°/35°		38°/55°		2 excellent case,1 good cases,1 passable cases
Current study	5	3D printing metal prosthesis	cement	40.8	21.6°/20°	71.2°/50°	64.2%(compared to normal side)	Mayo scores 70	Distal radioulnar joint dislocation, impingement syndrome

one hand, special attention should be given to these ligaments during surgery, with an effort to preserve as much of the TFCC structure as possible. The remaining dorsal and palmar radial-ulnar ligaments should be sutured to the pre-made holes on the ulnar side of the prosthesis, and other preserved capsular structures and soft tissues should be sutured to the corresponding areas of the mesh patch. On the other hand, for patients in whom the TFCC structure cannot be preserved, autograft tendon repair should be attempted to reconstruct the radial-ulnar joint ligaments. Based on the origin and insertion points of the palmar and dorsal radial-ulnar ligaments, holes should be made on the ulnar side and in the pre-designed holes of the prosthesis, using autograft tendons to suture and reconstruct the key ligaments of the TFCC. This requires detailed preoperative discussion and planning. In the final patient of our study, while ensuring complete tumor excision, we effectively preserved and reconstructed the dorsal and palmar radioulnar ligaments of the TFCC using a mesh graft. During the subsequent 31-month follow-up, no radioulnar joint dislocations were observed, and the patient's wrist rotational function was near-normal (Fig. 3E).

Additionally, varying degrees of ulnar deviation of the wrist were observed in all 5 cases. This is a common issue, as previously reported. On one hand, it results from the destruction of the TFCC and incomplete reconstruction, leading to instability of the distal radioulnar joint (DRUJ). On the other hand, it is related to the positioning of the prosthesis. Misalignment during prosthesis placement may alter the normal physiological angle between the radius and the carpal bones, causing misalignment of the contact surface between the ulna and radius, which in turn leads to DRUJ instability and ulnar deviation. Previous studies, such as those by Tu et al. [20], using clinical review and biomechanical analysis, divided patients into two groups based on the palm tilt angle within the prosthesis: the biological angle (BA) group and the zero-degree (ZD) group. They ultimately found that the incidence of radiocarpal subluxation and distal radioulnar joint dislocation was lower in the zero-degree group. This provides valuable insight for further consideration, and more research is needed to explore this issue.

In one case, a patient with distal radioulnar joint dislocation developed ulnar impaction syndrome [21] (Fig. 2E), a condition triggered by positive ulnar variance, resulting in the ulna colliding with the lunate bone. Upon reviewing the patient's initial postoperative X-ray images (Fig. 2D), we observed that the ulnar articular surface was slightly anterior to the prosthesis surface, and the joint space had narrowed. With increased wrist rotational activities and the occurrence of radioulnar joint dislocation, the ulnar variance intensified, ultimately leading to ulnar impaction. Therefore, the precision of the preoperative prosthetic design is critical; the osteotomy length must closely match the prosthetic size. It is recommended to perform multiple X-ray fluoroscopy checks intraoperatively to ensure proper alignment of the prosthesis with the ulnar notch. For cases where the prosthesis is too long, increasing the osteotomy length is advisable; if the prosthesis is too short, using bone cement or grafting to secure its correct position is recommended to minimize the risks of ulnar variance and postoperative complications such as ulnar impaction syndrome and degenerative bone changes.

Limitations

This study demonstrates the potential efficacy of using 3D-printed fully metal prostheses combined with mesh grafts in treating giant cell tumors of the distal radius. However, the study has several limitations. Firstly, the sample size is small, and the results may not be representative of the entire patient population. Secondly, the follow-up period of the study is insufficient to evaluate long-term complications, particularly changes in joint surface degeneration and the durability of the prostheses, which require longer-term follow-up observation. These limitations suggest that further research validation and longer follow-up observation are needed before widespread application of this treatment method.

Conclusion

This study employed en bloc resection combined with 3D-printed, fully integrated metallic distal radial prostheses and mesh grafts to treat Campanacci Grade III or recurrent giant cell tumors of the distal radius, achieving acceptable outcomes and demonstrating that this approach is a viable treatment option for patients. The design optimizations, including the fully integrated metallic prosthesis, pre-fabricated holes, trabecular collars, and highly compatible articular surfaces, have proven to be rational and effective. Additionally, the use of mesh grafts facilitates the reconstruction of surrounding soft tissues, accelerating postoperative functional recovery and exercise. Intraoperative preservation or reconstruction of the triangular fibrocartilage complex, particularly the dorsal and palmar radioulnar ligaments, is crucial for preventing dislocation of the distal radioulnar joint. Moreover, ensuring that the osteotomy length matches the prosthesis size is key to minimizing the risk of impaction syndrome.

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Author contributions
Tianwen Zhang and XiaoNing Tan conceived the study and drafted the manuscript; Zhenchao Yuan, Bin Liu andJiachang Tan participated in the study design and interpretation. All authors read and approved the final manuscript.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
This study was approved by the ethical review committee of the Cancer Hospital of Guangxi Medical University in accordance with the principles of the Helsinki Declaration. In this retrospective study, all data remained anonymous, and the requirement for written informed consent from patients was waived. Written informed consent from participants was not required in accordance with local/national guidelines.

Human ethics
Not applicable.

Competing interests
The authors declare no competing interests.

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