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REVIEW ARTICLE

Wrist Reconstruction after En bloc Resection of Bone Tumors of the Distal Radius

Weijian Liu, MA[1], Baichuan Wang, MD[1], Shuo Zhang, MA[1], Yubin Li, MA[2], Binwu Hu, MD[1], Zengwu Shao, MD[1]

[1]*Department of Orthopaedics, Union Hospital, Tongji Medical College, Huazhong University of Science and Technology, Wuhan and* [2]*Department of Orthopaedics, Linqing City People's Hospital, Linqing, China*

Wrist reconstruction after en bloc resection of bone tumors of the distal radius has been a great challenge. Although many techniques have been used for the reconstruction of long bone defects following *en bloc* resection of the distal radius, the optimal reconstruction method remains controversial. This is the first review to systematically describe various reconstruction techniques. We not only discuss the indications, functional outcomes, and complications of these reconstruction techniques but also review the technical refinement strategies for improving the stability of the wrist joint.

En bloc resection should be performed for Campanacci grade III giant cell tumors (GCT) as well as malignant tumors of the distal radius. However, wrist reconstruction after en bloc resection of the distal radius represents a great challenge. Although several surgical techniques, either achieving a stable wrist by arthrodesis or reconstructing a flexible wrist by arthroplasty, have been reported, the optimal reconstruction procedure remains controversial. The purpose of this review was to investigate which reconstruction methods might be the best option by analyzing the indications, techniques, limitations, and problems of different reconstruction methods. With the advancement of imaging, surgical techniques and materials, some reconstruction techniques have been further refined. Each of the techniques discussed in this review has its advantages and disadvantages. Wrist arthrodesis seems to be preferred over wrist arthroplasty in terms of grip strength and long-term complications, while wrist arthroplasty seems to be superior to wrist arthrodesis in terms of wrist motion. All things considered, wrist arthroplasty with a vascularized fibular head autograft might be a good option because of better wrist function, acceptable grip strength, and a relatively lower complication rate. Moreover, wrist arthrodesis is still an option if the fibular head autograft reconstruction fails. Orthopaedic oncologists should familiarize themselves with the characteristics of each technique to select the most appropriate reconstruction method depending on each patient's situation.

Key words: Arthrodesis; Arthroplasty; Distal radius tumor; En bloc resection; Wrist reconstruction

Introduction

The distal radius is an uncommon site for primary as well as metastatic bone tumors. Giant cell tumors (GCT) of the bone, benign tumors with potential invasiveness, are the most common tumors of the distal radius but only account for 10%–12% of all GCT of bone[1, 2]. Some malignant tumors in the distal radius, such as angiosarcoma, osteosarcoma, chondrosarcoma, and metastatic tumors, have only been reported sporadically in previous literature[3–6]. For the patients with Campanacci grade III GCT of the distal radius, en bloc resection of the tumor is often chosen because tumors in this location have a higher risk of local recurrence and a greater lung metastasis rate compared to tumors of other sites[7–9]. For malignant tumors of the distal radius, en bloc resection of the tumor with a wide margin should be performed according to cancer surgery principles.

Address for correspondence Zeng Wu Shao, MD, Department of Orthopaedics, Union Hospital, Tongji Medical College, Huazhong University of Science and Technology, 1277 Jiefang Road, Wuhan, China 430022, Tel and Fax numbers: 027-85351686.; Email: szwpro@163.com; Baichuan Wang, MD, Department of Orthopaedics, Union Hospital, Tongji Medical College, Huazhong University of Science and Technology, 1277 Jiefang Road, Wuhan, China 430022, Tel and Fax numbers: 027-85351686.; Email: wangbaichuan-112@163.com

Weijian Liu, Baichuan Wang and Shuo Zhang contributed equally to this work.

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The wrist reconstruction following en bloc resection of the bone tumor of the distal radius has been a great challenge for orthopaedic oncologists because of high functional demands of the wrist. Many techniques have been used for reconstructing such long bone defects[10, 11], but orthopaedic oncologists are not in agreement about the optimal procedure. The techniques, including (i) total wrist arthrodesis, (ii) partial wrist arthrodesis, (iii) osteoarticular allograft implantation, (iv) non-vascularized or vascularized fibula autograft implantation, and (v) prosthesis replacement, can be divided into two major categories: arthrodesis or arthroplasty. To the best of our knowledge, this report is the first review that systematically describes the various reconstruction techniques. In this review, we not only discuss the indications, functional outcomes, and complications of each reconstruction technique but also review technical refinement strategies to improve the stability of the wrist joint. Each of the techniques discussed in this review has its advantages and disadvantages. Wrist arthrodesis seems to be preferred over wrist arthroplasty in terms of grip strength and long-term complications, while wrist arthroplasty seems to be superior to wrist arthrodesis in terms of wrist motion. All things considered, wrist arthroplasty with a vascularized fibular head autograft might be a good option because of better wrist function, acceptable grip strength, and a relatively lower complication rate. Of note, wrist arthrodesis is still an option if the fibular head autograft reconstruction fails. Orthopaedic oncologists should familiarize themselves with the characteristics of each technique to select the most appropriate reconstruction method depending on each patient's situation.

Total Wrist Arthrodesis

Total wrist arthrodesis can result in a stable wrist that is free of pain; it can prevent some arthroplasty-related complications, such as subluxation, dislocation, and degenerative changes in the wrist joint, as well as pain caused by such complications. Therefore, this reconstruction technique is often applied in patients who have to engage in heavy physical activity. Moreover, total wrist arthrodesis is preferred when wrist arthroplasty fails[12–14]. Previous studies have described total wrist arthrodesis techniques, including fixation of the native radius and carpal-metacarpal with a bridging graft, with translocated ulna as well as fusion by ulna centralization (Fig. 1).

Bridging grafts include allograft, fibula autograft, and structure iliac crest bone grafts (ICBG)[15–17]. Total wrist arthrodesis with massive allograft possesses several advantages, such as being a simple surgical procedure and avoiding donor-site morbidity. However, allograft has obvious disadvantages, such as nonunion and fracture[18, 19]. That is why some surgeons, including us, do not like the allograft reconstruction. The autogenous grafts are more popular. Qu *et al.* treated eight patients with a total wrist arthrodesis with the use of fibula autograft, and they reported that wrist arthrodesis provided better grip strength and functional outcomes than wrist arthroplasty[16]. However, such a reconstruction may bring complications associated with obtaining an autologous fibular graft[20]. Wang *et al.* selected to apply total wrist fusion with autogenous structural ICBG because of low donor-site morbidity. Their results showed that the reconstructive technique can achieve favorable functional outcomes with a low complication rate[17]. However, ICBG can only be used when the bone defect is less than 8 cm; the fusion might fail with a shorter length of ICBG[21].

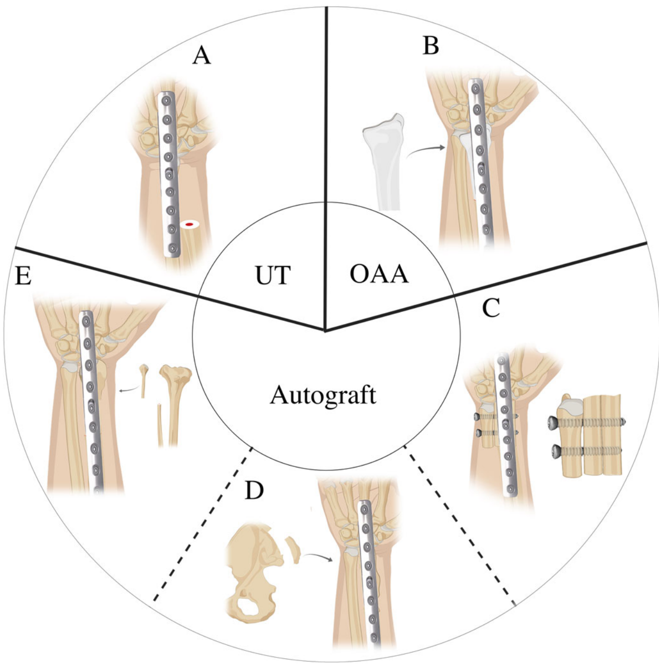

Fig 1 The commonly used wrist arthrodesis. (A) Ulna translocation (UT), (B) osteoarticular allograft (OAA), (C) ipsilateral double barrel segmental ulna autograft reconstruction with S-K procedure, (D) structural iliac autograft reconstruction, and (E) fibular autograft reconstruction.

Total wrist arthrodesis with ulnocarpal fusion or ulnar translocation is another alternative. The ulnocarpal fusion technique was first reported in the year 1921, before being modified by Greenwood in 1932[22]. Since then, it has been widely used for the reconstruction of large segment defects of the radius secondary to congenital absence, trauma, infection, as well as tumor resection[23]. Bhagat *et al.* used this technology to treat 25 patients with distal radius GCT; they concluded that most patients achieved satisfactory function, with 65% grip strength compared to the healthy side[24]. Although the procedure is simple and achieves acceptable grip strength, the loss of forearm rotation may limit its application. Ulnar translocation serves as a solution to address this issue[25]. The adjacent distal ulna was transferred with its retained muscle attached to the bony defect that was left after resection of the distal radius; in this way, a microvascular procedure can be avoided and the blood supply of the translocated graft is retained. Chalidis *et al.* reported that ulnar translocation for the treatment of GCT of the distal radius helped to retain rotation of the forearm and good function of the hand[26]. However, the postoperative cosmetic result was poor and the translocated ulna was too thin to withstand the stress of strenuous activities. Zhang *et al.* reported a modified ulnar translocation technology, in which an ipsilateral double barrel segmental ulnar bone graft combined with an S-K procedure (discussed later) was proposed for the treatment of the GCT of the distal radius. The results showed that the procedure facilitated the recovery of grip strength with fewer functional deficits and a lower rate of complications[27]. Such a one-bone forearm reconstruction technique may be a better option in cases where the extensive soft-tissue involvement has resulted in loss of soft tissue and skin. (Table 1).

Partial Wrist Arthrodesis

Although total arthrodesis could provide a stable and powerful wrist joint, the loss of wrist motion can make it difficult for patients to perform daily activities. Partial wrist arthrodesis helps to preserve the metacarpal joint, thus ensuring a better quality of life. There are three types of partial wrist arthrodesis: radio-lunate fusion, radio-scaphoid fusion, and radio-scaphoid-lunate fusion[28]. Of these, the radio–scaphoid–lunate fusion showed similar biomechanical behavior when compared with the healthy wrist[29]. Bickert *et al.* reported two cases of malignant tumors of the distal radius treated with fibulo–scapho–lunate arthrodesis; excellent functional and radiological outcomes were observed[30]. Zhu *et al.* (2013) compared the functional and radiographic outcomes between partial wrist arthrodesis (fibulo–scapho–lunate fusion) and wrist arthroplasty. They found that partial wrist fusion resulted in a durable and stable wrist with acceptable wrist motion, good long-term functional outcome, and low complication rate[31]. In addition to the commonly used fibular autograft, the tibia cortical strut autograft (TCSA) was also used for partial wrist arthrodesis, as a substitute. In 1975, Campbell *et al.* first described an arthrodesis technique in which a tibial strut autograft was fused with the first carpal row to perform a partial wrist arthrodesis[32]. van de Sande *et al.* (2013) reported an adapted TCSA wrist arthrodesis

TABLE 1 Wrist arthrodesis after en-bloc resection of bone tumors of the distal radius

Reconstruction		Author	Cases	Follow-up (months)	Functional outcomes	Complications
Total arthrodesis	Non-vascularized fibula	Qu *et al.*[16]	8	80	MSTS 93%, DASH score 8, grip strength 71%	Fracture (12.5%)
	Vascularized Bone Grafts	Clarkson *et al.*[21]	14	>12	MSTS 80%, DASH score 20	Peroneal nerve palsy (14.3%), flap necrosis (7.2%)
	ICBG	Wang *et al.*[17]	27	56	MSTS 96%, DASH score 9, grip strength 51%	Fracture (3.7%), hardware failure (14.8%), nonunion (7.4%), hardware loosening (3.7%)
	ICBG	Clarkson *et al.*[21]	13	>12	MSTS 90%, DASH score 17	Infections (15.4%)
	Segmental ulna graft	Zhang *et al.*[27]	8	36	MSTS 83.3%, DASH score 48.9, grip strength 71%	Not mentioned
	Ulna centralization	Bhagat *et al.*[24]	25	28.8	grip strength 65%	Superficial wound infection (8%), additional bone grafting (8%)
	Ulnar translocation	Puri *et al.*[25]	14	26	MSTS 87%	Radio-ulnar synostosis (7.1%), fracture (7.1%)
	Various	Wysocki RW *et al.*[7]	11	153	MSTS 90%, DASH score 3, grip strength 77.6%	Nonunion (25%)
Partial arthrodesis	Tibia cortical strut autograft	van de Sande *et al.*[6]	17	32	MSTS 71.7%, DASH score 9.2, grip strength 75%	Fracture (5.9%)
	Non-vascularized/ vascularized fibula	Zhu *et al.*[31]	7	47.1	MSTS 85.3%, grip strength 76.5%	Fracture (28.6%)

ICBG, iliac crest bone grafts; MSTS, musculoskeletal tumor society scoring; DASH: disability of arm shoulder and hand scoring.

TABLE 2 Wrist arthroplasty after en-bloc resection of bone tumors of the distal radius

Reconstruction	Authors	Cases	Follow-up (months)	Functional outcomes	Complications
Osteoarticular allograft	Asavamongkolkul *et al.*[18]	8	60	MSTS 93%, grip strength 72.2%	Nonunion (25%), fracture (12.5%), pain (12.5%)
	Bianchi *et al.*[19]	12	52	MSTS 91.7%	Nonunion (8.3%), joint instability (66.7%), subchondral bone alterations (100%)
	Duan *et al.*[34]	15	62.4	Mayo score 70, grip strength 27 hg	Pain (6.7%), degenerative changes (100%)
	Scoccianti *et al.*[35]	17	58.9	MSTS 86%	Fracture (5.9%), degenerative changes (100%)
	Kocher *et al.*[37]	24	130	Grip strength 64.8%	Fracture (16.7%), pain need revision (8.3%), tolerable pain (54%), volar dislocation (4.2%)
	Li *et al.*[40]	10	84.7	MSTS 72%, grip strength 57.3%	Fracture (40%), subluxation (30%), subchondral bone alterations (100%)
	van de Sande *et al.*[6]	7	32	MSTS 73.3%, DASH score 10.9, grip strength 80%	Plate loosening (14.3%), fracture (14.3%), nonunion (42.9%)
Vascularized fibula arthroplasty	Yang *et al.*[48]	17	51.6	Mayo Wrist scores 77.3, grip strength 77.2%	Pain (47%)
	Chung *et al.*[49]	12	75.1	MSTS 88%, grip strength 57.2%	Joint instability (41.7%)
	Liu *et al.*[50]	26	66.9	MSTS 92.3%, DASH score 9, grip strength 71%	subluxation (11%), graft resorption (11.1%) degenerative changes (19%)
	Innocenti *et al.*[62]	6	52.8	Unavailable	Peroneal nerve palsy (33.3%)
Non-vascularized fibula arthroplasty	Chadha M *et al.*[8]	9	56	Unavailable	Fracture (22.2%), subluxation (11.1%), graft resorption (11.1%)
	Saini R *et al.*[10]	12	69.6	MSTS 91.3%, grip strength 71%	Subluxation (25%), nonunion (16.7%)
	Qu *et al.*[16]	13	80	MSTS 83%, DASH score 17, grip strength 40%	Subluxation (30.7%), nonunion (7.7%), flap necrosis (7.7%), CPN paralysis (7.7%)
	Asavamongkolkul *et al.*[18]	7	60	MSTS 93%, grip strength 69%	Pain (28.6%)
	Humail *et al.*[46]	12	24	Grip strength 60%	Peroneal nerve palsy (16.7%), subluxation (16.7%), superficial wound infection (25%)
	Qi *et al.*[47]	12	39.6	MSTS 84.1%, DASH score 13, grip strength 55.2%	Carpal bone subluxation (25%), dislocation (8.3%), osteoarthritis (91.7%)
	Saikia *et al.*[45]	24	79.2	Grip strength 67%	Deep infection (4.1%), fracture (4.1%), subluxation (12.3%)
	Zhu *et al.*[31]	7	48	MSTS 86.3%, grip strength 59.2%	Subluxation (28.6%), degenerative change (57.1%)
Prosthesis replacement	Wang *et al.*[51]	10	52	Mayo Wrist scores 68, grip strength 68%	Loosening (10%), subluxation (20%), degenerative changes (30%)
	Zhang *et al.*[56]	11	55.5	MSTS 80.3%, grip strength 70.1%	Superficial infection (9%), tolerable pain (9%)
	Natarajan *et al.*[55]	24	78	MSTS 74%	Flap necrosis (8.3%), deep infection (8.3%)
	Lu *et al.*[60]	11	14.5	Mayo Wrist scores 72, DASH score 18.7, grip strength 69.9%	NA

MSTS, musculoskeletal tumor society scoring; DASH: disability of arm shoulder and hand scoring; CPN, common peroneal nerve.

surgical technique and compared it with osteoarticular allograft in terms of functional outcomes and complications. The results showed that TCSA wrist arthrodesis resulted in similar functional outcomes as other techniques but with a more stable wrist, and lower complication and donor site morbidity rates[6]. However, a problem for partial wrist arthrodesis is the limited fusion contact area; therefore, it requires long-term stable fixation to achieve bone union. Partial wrist arthrodesis might also lead to complications, such as infection, fracture, delayed union, and nonunion[33](Table 1).

Wrist Arthroplasty

Compared with wrist arthrodesis, the main advantage of a wrist arthroplasty is that it can provide a more flexible wrist joint, which helps to improve the patient's quality of life. However, in many previous studies, wrist arthrodesis appears

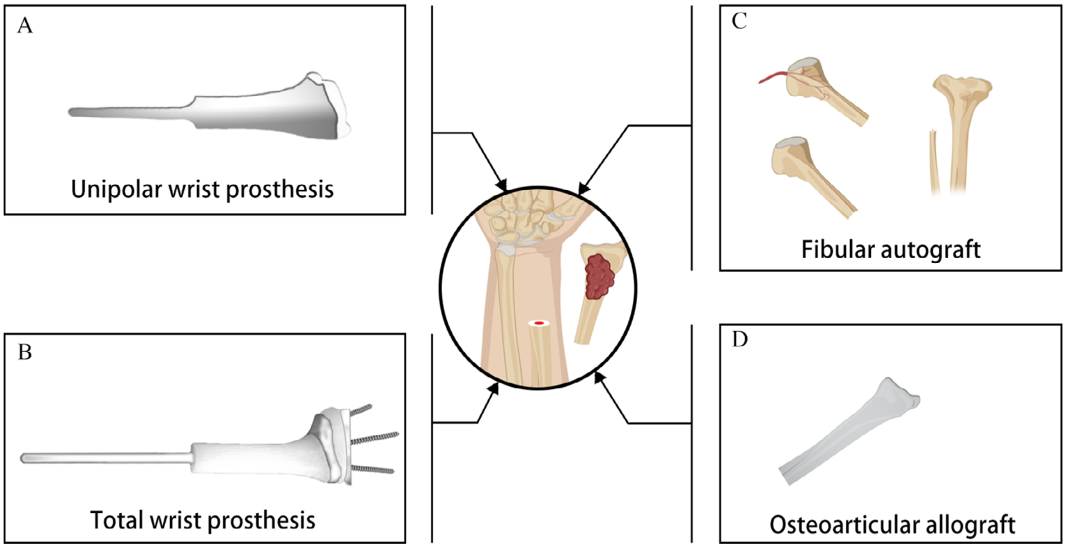

Fig 2 Wrist arthroplasty. Mechanical reconstruction: (A) Unipolar wrist prosthesis and (B) total wrist prosthesis. Biological reconstruction: (C) Vascularized or non-vascularized fibular autograft and (D) osteoarticular allograft.

to be superior to wrist arthroplasty in terms of musculoskeletal tumor society scoring (MSTS) and disability of arm shoulder and hand scoring (DASH) functional scores (Tables 1 and 2). The main reason is that both the scoring systems do not include an evaluation of wrist motion. A wrist-specific Mayo wrist score may be more objective and accurate for the evaluation of wrist function after reconstruction. (Fig. 2).

Osteoarticular Allograft Arthroplasty

Wrist reconstruction with a massive osteoarticular allograft was favored after the resection of the distal radius because of its perfect wrist-specific matching, no case of donor-site morbidity, as well as good to excellent functional results. Duan *et al.* described 15 patients who were treated by osteoarticular allograft reconstruction after tumor resection of the distal radius; they concluded that osteoarticular allograft reconstruction resulted in satisfactory wrist function[34]. In another study with 17 patients with tumors of the distal radius, researchers found that after a mean follow up of 58.9 months, the function of the reconstructed wrist joint was acceptable, with a mean ISOLS-MSTS score of 86%[35]. Although good postoperative wrist function was reported, osteoarticular allograft reconstruction has been associated with high complication rates, including fractures, nonunion, and bony resorption. Allograft fractures are one of the most commonly seen complications. The prevalence of allograft fractures could ranges from 5.9% to 26.7%[35–37]. Previous studies showed that an appropriate plate length can provide extra-cortical support for allografts, and decrease the allograft fracture rate[38, 39]. To protect the massive osteoarticular allograft, Duan *et al.* used a locking compression plate (LCP) long enough to span the whole allograft and no fracture was observed in their patients. They also reported that the use of an LCP for allografts to host junction fixation resulted in a lower rate of allograft fracture than that of standard compression plate[34]. The incidence of allograft host junction nonunion is reported to range from 0% to 42.9%[6, 18, 34], and bone resorption as 11.7%[18, 19, 35]. In addition, some common complications, such as infection and allograft rejection, often occurred in other sites with allograft reconstruction but were relatively rare in distal radius allografts[3, 40]. One possible explanation is that the distal radius allograft has a relatively small volume. It is worth noting that the function of the reconstructed wrist might deteriorate with time because of the inevitable degenerative changes in an allograft. Bianchi *et al.* used the osteoarticular allograft to treat 12 patients with distal radius tumors. After a minimum follow up of 24 months (range 26–145 months), all patients underwent subchondral bone alterations and joint narrowing[19].

Fibula Autograft Arthroplasty

The use of fibular head autograft has been favored because of the anatomic similarities between the distal radius and the proximal fibula. In 1979, Pho *et al.* first used a free vascularized fibular head graft to reconstruct the long bone defect following tumor resection of the distal radius[41]. Since then, this technology has become a commonly used procedure for reconstructing the articular surface and large bone defects after resection of the distal radius[42–45]. A fibular head autograft for the distal radius reconstruction is used: a non-vascularized fibular head autograft or a vascularized fibular head autograft. Although many studies have described good and excellent results for wrist arthroplasty using a non-vascularized fibular head autograft, this reconstruction technique is associated with nonunion, delayed union of the graft, bone resorption, and secondary bony collapse of the grafted fibular head[46, 47]. Due to its independent vascularity, the vascularized fibular head autograft could be another alternative, especially when the defect is greater than 10 cm[21]. It not only provides similar functional outcomes to that of non-vascularized fibular head autograft reconstruction but also enables early healing and prevents bony collapse caused by insufficient blood flow from the transplanted fibular head. Yang *et al.* and Chung *et al.* reported that the vascularized fibular head autograft for reconstruction of the distal radius after tumor resection resulted in good functional outcome, with a shorter fusion time and higher fusion rate and no complication of bone resorption or collapse of the transplanted fibular head[48–50]. However, this method is quite technically challenging and time-consuming, and expertise is required to perform this procedure. For the vascularized/non-vascularized fibular head autograft reconstruction, instability of the wrist joint is the common complication. Some soft tissue reconstruction technologies have been used for enhancing the stability of the wrist (discussed later). Moreover, progressive degenerative changes are inevitable due to an incongruity between the fibular head and the proximal carpal row. However, the degenerative changes might be slight in children because of joint-surface remodeling of the proximal fibular epiphysis[51]. Although donor site complications, such as peroneal nerve palsy, were also observed[20, 46], they are rare and usually transient.

Prosthesis Replacement

Although wrist reconstruction with the use of a prosthesis is less frequent than other reconstruction methods, it serves as an alternative for patients with concerns regarding morbidity associated with harvesting fibular head autografts, and for cases where allograft is not available. Prosthetic replacement is also a sensible choice for patients with limited life expectancy. The main advantage of this reconstruction technique is that it can repair the long bone defects while avoiding graft-related complications, such as bone absorption, nonunion, delayed union, and donor-site morbidity[52]. There are two types of wrist prosthesis: unipolar prosthesis and total wrist prosthesis[53–55]. Although reasonable postoperative functional outcomes were reported in previous studies on unipolar prosthesis replacement, the relatively high complication rate should be considered. In our previous research, we used a custom-made unipolar prosthesis to reconstruct the wrist joint, and obtained an acceptable functional outcome with a mean Mayo wrist score of 68 and 68% grip strength of a normal hand. However, 60% of patients suffered from prosthesis-related complications[51]. Inconsistent with the findings of many previous studies, Zhang *et al.* did not find any prosthesis-related complications in their patients who underwent wrist reconstruction using custom-made unipolar prostheses[56].

Subluxation is one of the most frequently occurring complications in patients with unipolar hemiarthroplasty. To provide a more stable wrist joint, use of a total wrist prosthesis has been attempted to reconstruct the wrist joint following the resection of the distal radius. Damert *et al.* and Hariri *et al.* reported that the total wrist prosthesis replacement resulted in good postoperative function with a relatively stable wrist joint[57, 58]. However, Sargazi *et al.* reported that two cases with a total wrist prosthesis required revision surgery because of unsuccessful wrist arthroplasty.[12] All the studies discussed above are individual case reports, so it is difficult to draw an objective conclusion. Aseptic loosening is the most common cause of failure of prosthesis replacement. In therapy, the "mechanical-biological" reconstruction based on three-dimensional (3D) technology might greatly reduce the incidence rate of prosthesis loosening[59]. In Lu *et al.* (2018), an uncemented, 3D-printed personalized prosthesis was used to reconstruct the wrist joint, and obtained acceptable postoperative functional outcomes without prosthesis-associated complications[60]. However, the follow up was only 14.45 months on average. Moreover, degenerative changes in the reconstructed wrist seem to be inevitable, which might be attributed to the reduced wrist motion and incompatible contact between the prosthesis and bone. (Table 2).

Technical Refinement for Stability of the Reconstructed Wrist

Instability of the reconstructed joint often occurs after wrist arthroplasty, which might cause pain, decrease grip strength, and limit the wrist function[42, 61]. Wrist ligaments, the capsule, the triangular fibrocartilage complex (TFCC), the distal interosseous membrane (DIOM), and muscle play important roles in maintaining the stability of the wrist[44]. Some of these structures could be injured/excised during the tumor resection process. Innocenti *et al.* provide a soft tissue reconstruction strategy. In their report, the biceps femoris tendon that remains attached to the fibular head was woven into the distal capsule and ligaments and was then anchored to a residual portion of the interosseous membrane[62]. Other soft tissue reconstruction strategies, including the use of the fibular head capsule, the lateral collateral ligament, or the flexor carpi radialis tendon, were also reported in previous studies[43, 63–65]. In addition, the Adams and Berger procedure, involving a tendon graft reconstruction through bone tunnels, could be applied to improve the stability of the distal radio-ulnar joint (DRUJ)[66].

In addition to soft tissue reconstruction, the intact three-column structure is critical for maintaining the stability of the wrist joint, which enables the wrist to be more stable and powerful as well as delay the arthritis caused by fretting wear[67]. Based on this concept, Szabo *et al.* reported a procedure in which a distal radial osteochondral allograft was combined with DRUJ arthrodesis through ulnar osteotomy (the S-K procedure). They performed this procedure in nine patients and found that it contributed to functional stable wrist motion and decreased late collapse of the allograft[36]. Li *et al.* (2015) analyzed the effects of the S-K procedure on functional results after en bloc resection of distal radial tumors and osteoarticular allograft reconstruction. They found that patients who underwent the S-K procedure had better range of rotation, greater grip power, and less degenerative changes than those not undergoing the S-K procedure[40].

Conclusion

Many techniques have been used for wrist reconstruction after en bloc resection of bone tumors of the distal radius. Each of the techniques has its advantages and disadvantages. Based on this review and our experiences, wrist arthroplasty with a vascularized fibular head autograft might be a good option because of the resulting better wrist function, acceptable grip strength, and relatively lower complication rate. Wrist arthrodesis is still an option even if the fibular head autograft reconstruction fails. However, more importantly, orthopaedic oncologists should familiarize themselves with each technique to select the most appropriate individualized reconstruction method based on each patient's situation.

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