



ELBOW

Megaprosthetic replacement of the distal humerus: still a challenge in limb salvage



Marcel-Philipp Henrichs, MD^{a,b,*}, Dennis Liem, MD^a, Georg Gosheger, MD^a,
Arne Streitbueger, MD^{a,c}, Markus Nottrott, PhD^a, Dimosthenis Andreou, MD^a,
Jendrik Harges, MD^{a,c}

^aDepartment of Orthopedics and Tumor Orthopedics, Muenster University Hospital, Münster, Germany

^bDepartment of Orthopedics and Special Orthopedic Surgery, Paracelsus-Klinik Osnabrück, Osnabrück, Germany

^cDepartment of Musculoskeletal Surgical Oncology, Essen University Hospital, Essen, Germany

Background: The distal humerus is a rare location of bone tumors. Because of the complexity of the elbow joint, poor soft-tissue coverage, and proximity of nerves and vessels, resection and endoprosthesis reconstruction are demanding.

Methods: This retrospective study evaluated the clinical results after distal humeral resection and megaprosthetic reconstruction in 12 patients with an average age of 46 years. All patient files were reviewed for clinical information, and postoperative function and patients' contentment were assessed using the Musculoskeletal Tumor Society score.

Results: The predominant diagnoses were bone and soft-tissue sarcoma (n = 6), giant cell tumor (n = 2), and renal cell carcinoma metastasis (n = 2). Local recurrence was the reason for secondary amputation in all cases (n = 3). The prosthetic survival rate after surgery was 82% at 2 years and 64% at 5 years. Reconstruction failure was mainly caused by aseptic loosening of the humeral stem, occurring in 27% (n = 3), followed by aseptic loosening of the ulnar stem in 9% (n = 1) and periprosthetic infection in 9% (n = 1). The mean Musculoskeletal Tumor Society score was 24 points (range, 20–30 points). An extension lag of more than 10° was noted in 6 patients (55%).

Conclusion: Our results suggest that limb salvage with a distal humeral replacement can achieve good functional results in most patients, although the complication rate with special emphasis on the loosening rate of the humeral stem is high. However, limb salvage was not achieved in 27% of patients because of local recurrence.

Level of evidence: Level IV; Case Series; Treatment Study

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Keywords: Distal humerus; elbow; bone tumor; megaprosthesis; limb salvage; soft-tissue tumor

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*Reprint requests: Marcel-Philipp Henrichs, MD, Department of Orthopedics and Special Orthopedic Surgery, Paracelsus-Klinik Osnabrück, Am Natruer Holz 69, Osnabrück 49069, Germany.

E-mail address: mp.henrichs@gmail.com (M.-P. Henrichs).

Bone and soft-tissue tumors around the elbow are rare.^{4,28} About 1% of primary bone lesions and bone metastases arise in the distal humerus.^{14,17} The main goal in sarcoma surgery is a wide resection of the tumor (resection with clear margins), whereas in benign tumors and bone metastases, a marginal or even intralesional resection may be sufficient. However, in these cases, tumor resection results in bone defects that

are difficult to treat.¹⁴ In addition, resection at this location can lead to temporary or even permanent palsy, which is favored by the proximity of the tumor and nerves. Wide tumor resection impairs already poor soft-tissue conditions. Several different approaches for reconstruction including allografts, allograft prosthetic composites (APCs), and a variety of prostheses have been reported.^{25,30} In this study, we focus on reconstruction with a modular tumor endoprosthesis, which is an accepted treatment for this condition.^{6,7,14} Soft-tissue coverage and a sufficient bone stock are crucial to endoprosthesis reconstruction. Maintenance of elbow function significantly contributes to the patient's quality of life. Only a few studies describing the results of tumor prostheses around the elbow are available.^{14,21}

The aim of this study was to report on the results of patients treated by this method with a special emphasis on the complication rate and the oncologic and functional results.

Materials and methods

We identified 12 patients (6 female and 6 male patients) treated with a distal humeral modular prosthetic reconstruction between 1998 and 2014 at our institution (Table I). All patients with total humeral reconstructions, 1 patient with a total elbow reconstruction, and 1 patient treated for aplasia of the elbow were excluded from the study. The average age at the time of implantation was 45 years (range, 22-73 years). The mean follow-up time was 91 months (range, 13-229 months; median, 68 months). As patient 12 (Table I) was lost to follow-up within the first month after surgery, this patient was excluded from further analysis.

All patients were traced by the institutional tumor database. Patient files were reviewed for clinical information. Biplanar radiographs obtained at every follow-up visit were evaluated for prosthetic failure and tumor recurrence. Follow-up for all patients was performed at our institution.

The diagnoses were as follows: osteosarcoma (n = 1), Ewing sarcoma (n = 2), pleomorphic sarcoma of bone (n = 1), grade III soft-tissue sarcoma (n = 2), multiple myeloma (n = 1), renal cell carcinoma metastasis (n = 2), giant cell tumor of bone (n = 2), and aneurysmal bone cyst (n = 1) (Table I). At first presentation, the Enneking stage

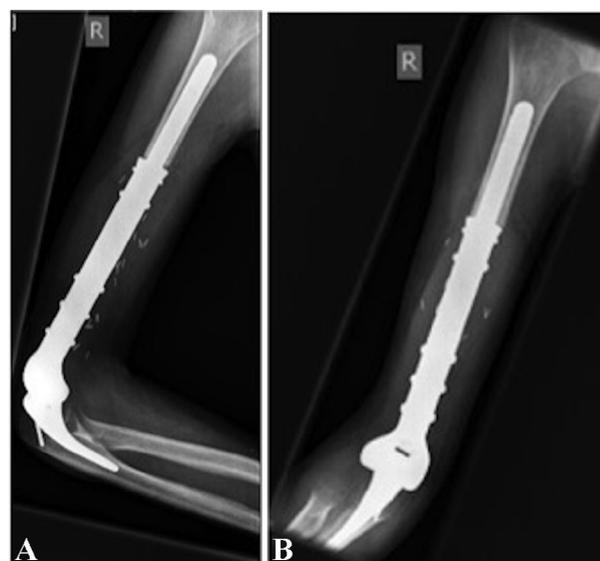


Figure 1 Plain radiographs of right arm: lateral (A) and antero-posterior (B) views. These radiographs show a distal humeral replacement with cementless fixation after resection of a Ewing sarcoma (patient 8, Table I).

of all sarcoma patients was IIB (n = 6).¹³ All patients with bone sarcomas received neoadjuvant and adjuvant chemotherapy according to international treatment protocols. In 1 of the Ewing sarcoma patients, adjuvant radiotherapy was performed aiming to reduce the risk of local recurrence after previous intralesional surgery. The patient with multiple myeloma presented with tumor recurrence after local radiotherapy. Both patients with renal cell carcinoma metastases received chemotherapy and radiotherapy postoperatively.

In 7 patients, tumor recurrence or inadequate previous surgery was the reason for distal humeral resection. Patient 8 was previously treated with curettage for Ewing sarcoma in another hospital (Figs. 1-4). In patient 5, a local recurrence developed after wide resection of a grade III soft-tissue sarcoma. The 2 patients with giant cell tumors of bone had local recurrence after intralesional curettage and bone cement filling (patients 4 and 7). The patient with an aneurysmal bone cyst underwent 3 intralesional curettages and, finally, a compound osteosynthesis because of extensive bone loss

Table I Patient demographic characteristics, previous surgical procedures, and follow-up

| Patient No. | Diagnosis | Age, yr | Follow-up, mo | Previous surgical procedures |
|-------------|------------------|---------|---------------|--|
| 1 | Osteosarcoma | 32 | 229 | None |
| 2 | RCC metastasis | 65 | 68 | Intralesional resection and osteosynthesis |
| 3 | Osseous UPS | 46 | 185 | None |
| 4 | GCT | 28 | 158 | Intralesional curettage (2 times) |
| 5 | STS | 71 | 17 | Wide resection |
| 6 | Multiple myeloma | 73 | 24 | Intralesional resection and osteosynthesis |
| 7 | GCT | 37 | 88 | Intralesional resection and cementation |
| 8 | Ewing sarcoma | 22 | 17 | Intralesional curettage |
| 9 | RCC metastasis | 72 | 13 | None |
| 10 | Ewing sarcoma | 21 | 170 | None |
| 11 | ABC | 26 | 31 | Multiple intralesional resections and osteosynthesis |
| 12 | STS | 60 | LTF | None |

RCC, renal cell carcinoma; UPS, undifferentiated pleomorphic sarcoma; GCT, giant cell tumor of bone; STS, soft-tissue sarcoma; ABC, aneurysmal bone cyst; LTF, lost to follow-up.



Figure 2 Plain radiograph of right arm: lateral view. Ten months after implantation, loosening of the humeral stem with consecutive shortening can be detected.



Figure 3 Plain radiograph, lateral view, showing right arm after surgical revision for loosening. The proximal bone stock had to be shortened, and a thicker hexagonal shaft was implanted. This revision shaft was designed with fins, aiming for better primary stability.

(patient 11). Two patients were initially treated by a palliative treatment regimen with intralesional curettage and compound osteosynthesis outside our center and presented with local recurrence and failure of the initial implant (patients 2 and 6, Table I).

Patient 9 presented with a pathologic fracture due to renal cell carcinoma metastasis. Because of massive bone destruction with joint involvement, marginal resection and reconstruction with a modular implant were performed.

The functional results were assessed according to the Musculoskeletal Tumor Society score (MSTS).¹² The upper-extremity version of this score contains the following 6 categories: pain, function, emotional acceptance, hand positioning, dexterity, and lifting ability. The maximum score adds up to 30 points (100%), which represents normal function. In case of secondary amputation, the last result available was used for analysis. The elbow range of motion was documented.

Eleven resections were performed by an S-shaped anterior approach and one by a posterior approach. An extra-articular resection



Figure 4 Computed tomography scan of right shoulder: axial slide (patient 8) shows an intraosseous soft-tissue mass proximal to the tip of the humeral stem (arrow). Computed tomography-guided needle biopsy revealed local recurrence of Ewing sarcoma 17 months after resection, leading to secondary amputation of the arm (P, posterior).

was performed in 3 cases. In all sarcoma patients, we aimed to achieve a wide resection with clear margins; in patients with metastases and benign tumors, a marginal resection was intended.

Defect reconstruction was performed with the Modular Universal Tumor and Revision System (MUTARS; Implantcast, Buxtehude, Germany), which is a modular fixed-hinge prosthesis with titanium components. Minimal humeral resection length for this reconstruction is 6 cm. The reconstruction length can be adjusted in steps of 2 cm. Adjustment of torsion is possible in steps of 10°. The hexagonal humeral stem was cemented in 4 cases; the ulnar stem, in 2 cases. In 4 patients, a silver-coated implant was used.

Postoperatively, all patients received an intravenous cephalosporin (cefuroxime) for 5 days. The elbow was immobilized in a sling for 2 weeks, but passive mobilization of the elbow with unrestricted extension was allowed immediately after surgery. At 2 weeks postoperatively, active mobilization was started.

The endpoints of the study were patient's death, secondary amputation owing to local recurrence, or prosthetic failure. Any event that led to an ablative surgical procedure (eg, local recurrence or prosthetic failure) was taken into account in the limb survival analysis. In contrast, the endpoints for prosthetic failure were aseptic loosening, stem fracture, and infection. Periprosthetic infection was diagnosed in accordance with the Centers for Disease Control and Prevention criteria. Written informed consent was obtained from every patient included in this study.

Results

Oncologic outcome

In all 6 sarcoma patients, a wide resection was achieved. In all other patients, a marginal resection of the tumor was

Table II Complications and oncologic and functional outcomes

| Patient No. | Complications | Timing of complication, mo | Secondary amputation | Oncologic outcome | MSTS score, points | ROM of elbow joint: flexion/extension, ° |
|-------------|---|----------------------------|----------------------|-------------------|--------------------|--|
| 1 | 1. Aseptic loosening of humeral stem 2. Periprosthetic infection | 122* 143* | No | NED | 25 | 150/0 |
| 2 | 1. Aseptic loosening of humeral stem 2. Local recurrence | 33* 66 | Yes | DOD | 20 | 115/35 |
| 3 | Aseptic loosening of ulnar stem | 11* and 185* | No | NED | 21 | 130/0 |
| 4 | None | | No | NED | 25 | 130/30 |
| 5 | Local recurrence | 17 | Yes | DOD | 30 | 130/0 |
| 6 | None | | No | DOD | 25 | 120/0 |
| 7 | None | | No | NED | 21 | 120/10 |
| 8 | 1. Aseptic loosening of humeral stem 2. Local recurrence | 10* 17 | Yes | NED | 29 | 120/15 |
| 9 | None | | No | AWD | 24 | 140/40 |
| 10 | Wound healing disturbance | 1* | No | NED | 25 | 130/40 |
| 11 | None | | No | NED | 24 | 100/30 |
| 12 | LTF | | Unknown | Unknown | Unknown | Unknown |

MSTS, Musculoskeletal Tumor Society score; ROM, range of motion; NED, no evidence of disease; DOD, died of disease; AWD, alive with disease; LTF, lost to follow-up.

* Surgical revision.

confirmed. As mentioned before, sufficient data for further analysis were available for 11 patients.

Of 8 patients with malignant lesions, 3 (38%) died of disease and 1 was alive with disease (Table II). The mean follow-up period was 136 months for the sarcoma patients ($n = 5$) compared with 35 months for the patients with widespread disease. Regarding these subgroups, 1 of 5 sarcoma patients died of disease (83 months after surgery) compared with 2 of 3 patients with widespread disease (mean of 58 months after surgery).

Regarding local tumor control, local recurrence developed in 3 of 8 patients (38%) with malignant lesions. Local recurrence occurred in 2 of 5 sarcoma patients 17 months after wide resection (patients 5 and 8, Table II). In addition, local recurrence developed in 1 patient with renal cell carcinoma metastasis 66 months after marginal resection (patient 2; 1 of 3 patients with widespread disease). However, in all 3 of these patients, the indication for distal humeral resection was local recurrence after intralesional ($n = 2$) or wide ($n = 1$) initial tumor resection in another hospital. All 3 patients with local

recurrence had to undergo amputation to achieve tumor control (Table II, Figs. 1-4). Of these 3 patients, 2 died of the malignancy and 1 was alive without disease. Despite previous intralesional resections, no patient with a benign tumor had a local recurrence after marginal tumor resection.

Functional results

The mean MSTS score ($n = 11$) was 24 points (range, 20-30 points; Table II), representing 80% of normal function. The mean arc of flexion was 108° (range, 70°-150°). An extension lag of more than 10° was noted in 6 patients (55%); 2 of them were still improving under intensive physiotherapy (Fig. 5).

Complications

Complications occurred in 6 of 11 patients (55%). In 5 patients (45%) with complications, revision was required, with

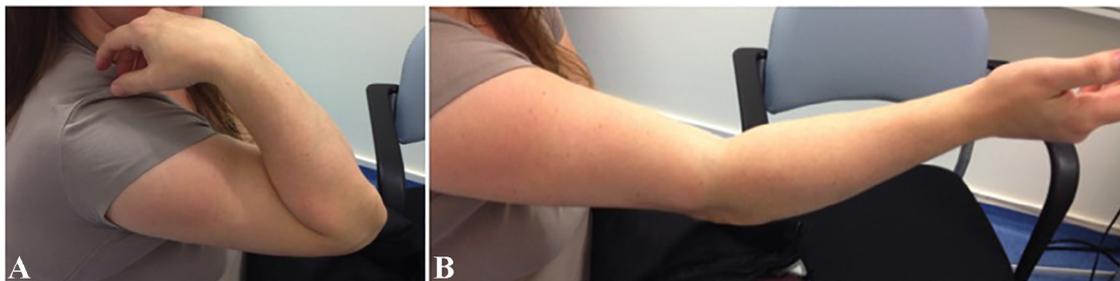


Figure 5 (A, B) Photographs of elbow joint showing range of motion more than 7 years after implantation of distal humeral prosthesis. Good flexion of 130° can be observed; the extension lag is around 30°. The Musculoskeletal Tumor Society score is 25 points.

multiple revisions being necessary in 2 cases (18%) (Table II). Major complications (prosthetic failure) occurred in 4 patients. The most common reason for failure in this group was aseptic loosening of the humeral stem, occurring in 3 patients. The median period between surgery and aseptic loosening was 33 months (range, 10-122 months). Patient 1 had aseptic loosening of the humeral stem at 122 months, which was treated by a cemented replantation, and septic stem loosening at 143 months with *Staphylococcus capitis*, which was treated successfully with a 1-stage reimplantation of the prosthesis. Aseptic loosening occurred in 2 of 6 patients (33%) treated with cementless humeral components and 1 of 4 patients (25%) treated with cemented humeral components. Other complications were aseptic loosening of the ulnar stem in 1 patient and periprosthetic infection in another.

Minor complications occurred in 5 patients. Three patients showed a temporary paresis of the radial nerve. In 1 patient, a neurolysis was performed but the paresis persisted. A wound healing disturbance developed in 1 patient and had to be treated with a free radialis flap. Taken together, the findings showed a prosthetic survival rate after surgery of 82% at 2 years and 64% at 5 years.

Discussion

Megaprosthesis reconstruction of the distal humerus is a rare procedure. In contrast to reconstruction at other anatomic sites, only a small number of cases have been reported in the literature (approximately 100).^{14,21,29} Therefore, our study with 12 patients treated between 1998 and 2014 contributes a relevant number of cases to the database of implanted and reported prostheses worldwide.

As reported in other studies, the indications for performing a distal humeral replacement showed a wide spectrum, ranging from bone and soft-tissue sarcoma, bone metastasis, and multiple myeloma to benign bone tumors.^{14,17,21} In addition to these diagnoses, Funovics et al¹⁴ included 15 patients treated for post-traumatic bone defects or failed primary arthroplasty, as well as patients who required total humeral reconstruction. To avoid an even more heterogeneous cohort, we excluded patients who received distal humeral resections for non-oncologic indications. In addition, patients with total humeral reconstruction were excluded, as we know that the shoulder function is massively impaired in these patients, which would affect functional scoring. Furthermore, the range of postoperative complications differs substantially.

Our study included 2 patients who were treated for recurrent giant cell tumor of bone. Today, the use of tumor prostheses in these cases is not the first-choice treatment anymore as patients have been successfully treated with denosumab.¹⁰ However, long-term results with respect to the use of denosumab in this condition are still lacking.

This cohort contained 3 patients with widespread disease. In these patients, the indication for resection and reconstruction with a modular implant has to be strict to avoid

overtreatment. In most cases, stabilization of the affected bone in combination with adjuvant therapy is sufficient. In 2 of our patients, tumor recurrence and implant failure after intralesional stabilization were the indications for resection. To achieve local control and enable a durable reconstruction, we decided to perform a marginal resection and to implant a megaprosthesis. One patient died of disease more than 2 years after surgery; the other patient had to undergo amputation more than 5 years after implantation. In a third patient, a huge renal cell carcinoma metastasis destroyed the elbow joint. As these metastases are frequently resistant to radiotherapy, we performed a marginal resection and implanted a modular prosthesis. Thirteen months after surgery, the patient was still alive with disease. Even though implantation of modular implants is a costly treatment in a palliative setting, it might be necessary to ensure a durable reconstruction.^{8,9,19}

In terms of local tumor control, it can be noted that resection of the distal humerus in addition to reconstruction with a megaprosthesis appears to be a safe treatment procedure. The main goal in orthopedic tumor surgery is adequate resection. The reconstruction one aspires to achieve should not jeopardize resection margins. The type of reconstruction itself does not influence the rate of recurrence or overall survival.⁷ This has recently been shown for other anatomic sites.¹

In our cohort, none of the patients with benign lesions had tumor recurrence despite previous multiple intralesional resections. In contrast, 3 patients with malignant primary or secondary tumors around the elbow were diagnosed with tumor recurrence during follow-up, resulting in a higher rate of relapse and consecutive secondary amputation than previously reported.^{17,21} This finding could be explained by the intralesional resection with which all of our patients had been treated initially and which carries a high risk of local tumor cell contamination.

These findings might imply that surgeons have only one chance to achieve local tumor control while aiming to preserve the limb in malignant bone tumors around the elbow, but with respect to the small number of patients, no general recommendation should be drawn. These results might raise the question of whether limb salvage has a worse oncologic outcome than primary amputation. In a study about osteosarcoma treatment, it was shown that limb salvage had a higher risk of local recurrence, which had no influence on disease-specific survival; other groups reported that there was no difference in oncologic outcome.^{2,5}

The functional results of patients with distal humeral replacement can be considered good to excellent. Our patients achieved a mean MSTS score of 24 points (80%). This is comparable to results published by other groups.^{6,14,17} All patients had active elbow flexion that enabled them to bring the hand to the mouth. A flexion deformity of 10° or more was observed in 6 patients without subjectively compromising function. A comparison of these functional results with the results of other reconstruction methods shows almost no difference. Aponte-Tinao et al³ reported their results of allograft reconstruction of the upper extremity. Their study contained

7 APC reconstructions of the elbow, which also achieved an average MSTTS score of 24 points. Similar results have been shown by Casadei et al⁷ and Schwab et al.²⁷ Kharrazi et al²⁰ reported the functional results after reconstruction with osteoarticular allografts of the elbow. In most tumor patients with a hemiarthral allograft reconstruction, satisfactory function was achieved.

Periprosthetic infection is the most common reason for secondary amputation after prosthetic reconstruction of the upper and lower extremity.¹⁸ In our study, however, local recurrence of malignant bone tumors was the only indication for secondary amputation, and periprosthetic infection occurred in only 1 patient (9%) but did not lead to a loss of the extremity. This is a noticeably low rate of periprosthetic infection, especially if multiple revisions that were necessary in some patients are taken into account. Funovics et al¹⁴ reported an infection rate of 15%, which led to an amputation in 1 patient. As they detected a higher infection rate for total humeral reconstructions, they concluded that the size of the implant influences the occurrence of infections.

Aseptic loosening of the humeral stem was the most common complication in our cohort (27% of patients), with a slightly higher loosening rate for uncemented stems (33%). Kulkarni et al²¹ reported a loosening rate for cemented humeral stems similar to our rate of 33%. The lowest loosening rate was reported by Funovics et al¹⁴ (8%). Focusing on the distal humerus only, loosening occurred in 4 of 41 patients (10%). Cementation was performed in 76% of patients. As our cases of loosening occurred after a mean period of more than 50 months, a mean follow-up period of 28 months might be too short to sufficiently detect long-term complications. In a very recent report, Goulding et al¹⁶ described their experiences with the use of a compressive osseointegration endoprosthesis in the upper extremity. In this multi-institutional study, they identified 7 patients who received a distal humeral endoprosthesis. Of these 7 patients, 6 encountered complications that required revisions; in 2 cases (29%), a structural failure of the compressive anchor occurred.

However, we hypothesized that the stem design certainly influenced the loosening rate. Therefore, we are now using longer stems (9 cm) with additional fins for a better press-fit implantation and the possibility to use locking screws. In doing so, we hope to reduce the torque, as well as rotational and tensile forces (Fig. 3). As in most other studies, loosening of the ulnar fixation was not a common problem. We observed 1 case of loosening after extra-articular resection, which was easily revised by cementless replantation of a custom-made stem.

It is interesting to note that, despite the poor muscle coverage in this region, we observed only 1 wound healing disturbance, which made a brachioradialis flap necessary. This finding is in line with most other published studies.^{14,17}

The revision rate of 46% in our patient cohort appears to be high. However, even in primary elbow arthroplasty for post-traumatic arthritis, rheumatoid arthritis, or primary osteoarthritis, revision rates between 5% in elderly patients with distal humeral

fractures and 54% in patients with an ankylosed elbow joint owing to rheumatoid arthritis or trauma have been reported.^{11,24} Considering the available studies on modular prostheses around the elbow that have described revision rates between 34% and 50%, we conclude that complications requiring surgical revision are a common problem.^{14,17}

There are reports of endoprosthesis reconstructions of the elbow with lower complication rates. Athwal et al⁴ reported a revision rate of 20% with the use of Coonrad-Morrey total elbow arthroplasty after resection of the distal humerus. The Coonrad-Morrey prosthesis was designed for primary and revision interventions and has shown good results for these indications.^{15,22,23} In the described cohort, 18 of 20 tumor resections were intralesional, saving bone stock for prosthetic anchorage. The main advantage of megaprotheses is the facility of restoring huge metaphyseal and diaphyseal defects, which is often required after wide resection of sarcomas. We think that the Coonrad-Morrey prosthesis is not suitable for reconstructing these extensive bone defects without combining it with an allograft (APC), as shown in other studies.^{7,27} In addition, it is known that the likelihood of complications is higher for megaprotheses compared with conventional prostheses.²⁶ A more recent study from Capanna et al⁶ reported low complication and revision rates. In a cohort of 36 patients, surgical revision was required in only 2 cases (1 structural failure and 1 deep infection). As known from other studies, the highest risk of implant failure is time from implantation.¹⁹ Because only 9 of the 36 patients reached a follow-up period of more than 24 months, conclusions on implant failure rates are difficult to draw.

Our study had several limitations. Indications for distal humeral resection are rare, which results in a small number of patients in our cohort, thereby restricting the power of the study because statistical analysis is not meaningful. In addition, follow-up periods are limited by the need for secondary amputation and/or death of patients. A minimum follow-up period of 24 months was achieved in 8 patients (73%). Finally, the retrospective character of this study limits the strength of our conclusions.

Conclusion

Modular prosthetic replacement of the distal humerus is a suitable treatment option for reconstruction after tumor resection. This treatment is associated with good functional results, but complications and high revision rates are very common. Wide resections of malignant tumors are crucial to avoid local recurrence and enable lasting limb salvage. Prosthetic survival was negatively influenced by the high rate of aseptic loosening of the humeral stem. Therefore, continuous efforts are needed to improve the design of the stems. In the future, implantation of longer and more structured stems should help reduce this complication.

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References

- Albergo JI, Gaston CL, Aponte-Tinao LA, Ayerza MA, Muscolo DL, Farfalli GL, et al. Proximal tibia reconstruction after bone tumor resection: are survivorship and outcomes of endoprosthetic replacement and osteoarticular allograft similar? *Clin Orthop Relat Res* 2017;475:676-82. <http://dx.doi.org/10.1007/s11999-016-4843-y>
- Andreou D, Bielack SS, Carrle D, Kevric M, Kotz R, Winkelmann W, et al. The influence of tumor- and treatment-related factors on the development of local recurrence in osteosarcoma after adequate surgery. An analysis of 1355 patients treated on neoadjuvant Cooperative Osteosarcoma Study Group protocols. *Ann Oncol* 2011;22:1228-35. <http://dx.doi.org/10.1093/annonc/mdq589>
- Aponte-Tinao LA, Ayerza MA, Muscolo DL, Farfalli GL. Allograft reconstruction for the treatment of musculoskeletal tumors of the upper extremity. *Sarcoma* 2013;2013:925413. <http://dx.doi.org/10.1155/2013/925413>
- Athwal GS, Chin PY, Adams RA, Morrey BF. Coonrad-Morrey total elbow arthroplasty for tumours of the distal humerus and elbow. *J Bone Joint Surg Br* 2005;87:1369-74. <http://dx.doi.org/10.1302/0301-620X.87B10.16569>
- Bacci G, Ferrari S, Lari S, Mercuri M, Donati D, Longhi A, et al. Osteosarcoma of the limb. Amputation or limb salvage in patients treated by neoadjuvant chemotherapy. *J Bone Joint Surg Br* 2002;84:88-92.
- Capanna R, Muratori F, Campo FR, D'Arienzo A, Frenos F, Beltrami G, et al. Modular megaprosthesis reconstruction for oncological and non-oncological resection of the elbow joint. *Injury* 2016;47(Suppl 4):S78-83. <http://dx.doi.org/10.1016/j.injury.2016.07.041>
- Casadei R, De Paolis M, Drago G, Romagnoli C, Donati D. Total elbow arthroplasty for primary and metastatic tumor. *Orthop Traumatol Surg Res* 2016;102:459-65. <http://dx.doi.org/10.1016/j.otsr.2015.12.026>
- Casadei R, Drago G, Di Pressa F, Donati D. Humeral metastasis of renal cancer: surgical options and review of literature. *Orthop Traumatol Surg Res* 2018;104:533-8. <http://dx.doi.org/10.1016/j.otsr.2018.03.009>
- Chandrasekar CR, Grimer RJ, Carter SR, Tillman RM, Abudu AT. Modular endoprosthetic replacement for metastatic tumours of the proximal femur. *J Orthop Surg* 2008;3:50. <http://dx.doi.org/10.1186/1749-799X-3-50>
- Chawla S, Henshaw R, Seeger L, Choy E, Blay JY, Ferrari S, et al. Safety and efficacy of denosumab for adults and skeletally mature adolescents with giant cell tumour of bone: interim analysis of an open-label, parallel-group, phase 2 study. *Lancet Oncol* 2013;14:901-8. [http://dx.doi.org/10.1016/S1470-2045\(13\)70277-8](http://dx.doi.org/10.1016/S1470-2045(13)70277-8)
- Cobb TK, Morrey BF. Total elbow arthroplasty as primary treatment for distal humeral fractures in elderly patients. *J Bone Joint Surg Am* 1997;79:826-32.
- Enneking WF, Dunham W, Gebhardt MC, Malawar M, Pritchard DJ. A system for the functional evaluation of reconstructive procedures after surgical treatment of tumors of the musculoskeletal system. *Clin Orthop Relat Res* 1993:241-6.
- Enneking WF, Spanier SS, Goodman MA. A system for the surgical staging of musculoskeletal sarcoma. *Clin Orthop Relat Res* 1980:106-20.
- Funovics PT, Schuh R, Adams SB Jr, Sabeti-Aschraf M, Dominkus M, Kotz RI. Modular prosthetic reconstruction of major bone defects of the distal end of the humerus. *J Bone Joint Surg Am* 2011;93:1064-74. <http://dx.doi.org/10.2106/JBJS.J.00239>
- Gill DR, Morrey BF. The Coonrad-Morrey total elbow arthroplasty in patients who have rheumatoid arthritis. A ten to fifteen-year follow-up study. *J Bone Joint Surg Am* 1998;80:1327-35.
- Goulding KA, Schwartz A, Hatstrup SJ, Randall RL, Lee D, Rispoli DM, et al. Use of compressive osseointegration endoprostheses for massive bone loss from tumor and failed arthroplasty: a viable option in the upper extremity. *Clin Orthop Relat Res* 2017;475:1702-11. <http://dx.doi.org/10.1007/s11999-017-5258-0>
- Hanna SA, David LA, Aston WJ, Gikas PD, Blunn GW, Cannon SR, et al. Endoprosthetic replacement of the distal humerus following resection of bone tumours. *J Bone Joint Surg Br* 2007;89:1498-503. <http://dx.doi.org/10.1302/0301-620X.89B11.19577>
- Hardes J, von Eiff C, Streitbueger A, Balke M, Budny T, Henrichs MP, et al. Reduction of periprosthetic infection with silver-coated megaprotheses in patients with bone sarcoma. *J Surg Oncol* 2010;101:389-95. <http://dx.doi.org/10.1002/jso.21498>
- Henrichs MP, Krebs J, Gosheger G, Streitbueger A, Nottrott M, Sauer T, et al. Modular tumor endoprostheses in surgical palliation of long-bone metastases: a reduction in tumor burden and a durable reconstruction. *World J Surg Oncol* 2014;12:330. <http://dx.doi.org/10.1186/1477-7819-12-330>
- Kharrazi FD, Busfield BT, Khorshad DS, Hornicek FJ, Mankin HJ. Osteoarticular and total elbow allograft reconstruction with severe bone loss. *Clin Orthop Relat Res* 2008;466:205-9. <http://dx.doi.org/10.1007/s11999-007-0011-8>
- Kulkarni A, Fiorenza F, Grimer RJ, Carter SR, Tillman RM. The results of endoprosthetic replacement for tumours of the distal humerus. *J Bone Joint Surg Br* 2003;85:240-3.
- Morrey BF, Adams RA. Semiconstrained elbow replacement for distal humeral nonunion. *J Bone Joint Surg Br* 1995;77:67-72.
- Morrey BF, Adams RA. Semiconstrained arthroplasty for the treatment of rheumatoid arthritis of the elbow. *J Bone Joint Surg Am* 1992;74:479-90.
- Peden JP, Morrey BF. Total elbow replacement for the management of the ankylosed or fused elbow. *J Bone Joint Surg Br* 2008;90:1198-204. <http://dx.doi.org/10.1302/0301-620X.90B9.19967>
- Renfree KJ, Dell PC, Kozin SH, Wright TW. Total elbow arthroplasty with massive composite allografts. *J Shoulder Elbow Surg* 2004;13:313-21. <https://doi.org/10.1016/j.jse.2004.01.010>
- Schmidt-Braekling T, Streitbueger A, Gosheger G, Boettner F, Nottrott M, Ahrens H, et al. Silver-coated megaprotheses: review of the literature. *Eur J Orthop Surg Traumatol* 2017;27:483-9. <http://dx.doi.org/10.1007/s00590-017-1933-9>
- Schwab JH, Healey JH, Athanasian EA. Wide en bloc extra-articular excision of the elbow for sarcoma with complex reconstruction. *J Bone Joint Surg Br* 2008;90:78-83. <http://dx.doi.org/10.1302/0301-620X.90B1.19958>
- Sperling JW, Pritchard DJ, Morrey BF. Total elbow arthroplasty after resection of tumors at the elbow. *Clin Orthop Relat Res* 1999:256-61.
- Tang X, Guo W, Yang R, Tang S, Yang Y. Custom-made prosthesis replacement for reconstruction of elbow after tumor resection. *J Shoulder Elbow Surg* 2009;18:796-803. <http://dx.doi.org/10.1016/j.jse.2009.01.022>
- Weber KL, Lin PP, Yasko AW. Complex segmental elbow reconstruction after tumor resection. *Clin Orthop Relat Res* 2003;31:44. <http://dx.doi.org/10.1097/01.blo.0000093894.12372.53>