OPERATIVE TECHNIQUE

Modified Masquelet Technique Assisting 3D Printed Elbow Prosthesis for Open Elbow Fracture with Severe Bone Defect: A Case Report and Technique Note

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Background: Internal fixation for severe open articular bone defects is sometimes ineffective or dangerous. In the emergency stage, radical debridement and infection prevention are demanded to provide a good tissue base and the space-occupying effect to provide enough necessary space to avoid soft-tissue contraction for the reconstruction. In addition, the 3D printing technology makes individual limb reconstruction a reality.

Case Presentation: Here, we present a 31-year-old patient with an open fracture and severe bone defect of his left elbow caused by traffic accident, classified as Gustilo–Anderson IIIB. We adopted aggressive debridement and insertion of polymethyl methacrylate (PMMA) to prevent the infection and temporarily construct the bone defect in the emergency stage. Secondly, the total elbow arthroplasty was performed using a unique three-dimensional (3D) printed prosthesis to reconstruct the elbow joint. During the follow-up, the elbow movement function was satisfactory.

Conclusions: The modified Masquelet technique assisting 3D printing of personalized elbow joint makes the satisfactory functional reconstruction for open high-energy injuries come true. It could be promoted for the similar surgery of other open joints fractures with severe bone defects.

Key words: bone defect; induced membrane technique; three-dimensional printed; prosthesis; total elbow arthroplasty

Introduction

The intra-articular fractures should be anatomically reduced and fixed to prevent the reduced range of motion, anchylosis, pain, and osteoarthritis, so the management of comminuted distal humerus fractures is a challenge for all orthopaedic surgeons.[1] In young patients with good bone quality, open reduction and internal fixation (ORIF) is the standard surgical treatment, while in elderly patients with low demand and osteoporosis, comminuted fractures are more common, so joint prosthesis replacement is often considered.[2] However, in some open injuries, the problem is further complicated by the traumatic segmental bone defects. Current treatment programs include Ilizarov technology, vascularized bone graft, traditional massive bone grafts, the Masquelet technique, artificial joint replacement, and even amputation.[3–10] The long disease course, complex treatment method, and the patients' inferior tolerance limit Ilizarov technology. The vascularized bone grafts can effectively repair bone defects but require a high degree of microsurgical skill. Traditional massive bone grafts are at high risk of being absorbed and have a poor effect on improving intra-articular bone loss.

Masquelet technique,[7,11,12] a two-stage technology known as induced membrane technique, has been applied and showed promising results in treating segmental bone defects. PMMA with mixed antibiotic (vancomycin usually) is implanted in the bone gap after wound debridement. Its presence serves a threefold function of effectively preventing

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secondary infection due to the slow release of vancomycin, preventing the fibers from growing into the bone gap, and inducing the formation of a membrane which is rich in capillary network, growth factors, and osteoinductive factors.[13,14] The standard second-stage Masquelet technique strictly follows the autologous implantation.

Total elbow arthroplasty (TEA) has been traditionally used for inflammatory arthropathy, but it has become an increasingly common treatment for trauma.[15,16] Studies reported that TEA could achieve a good or excellent functional outcome compared to ORIF in treating distal humerus fractures, especially for severely comminuted fractures, bone defect, destruction of the articular surface, or elbow instability.[2] Furthermore, the three-dimensional (3D) technique and 3D printed prosthesis have enabled elbow replacement to flourish, addressing the intractable problem of traumatic bone loss without redundant osteotomy. The prosthesis is designed and simulated to simplify the operation steps and achieve anatomical reconstruction. Nevertheless, prosthetic replacement is contraindicated for acute management of open fractures or patients with chronic infection.[1]

So, there is currently a lack of targeted treatment for open elbow fractures combined with severe bone defects. Kevin used 3D printed titanium cages combined with the Masquelet technique to reconstruct femoral segmental defects.[17] To our knowledge, there are no reports of the combination of induced membrane technique and 3D printed prosthesis replacement in the open intra-articular bone defects. We present a Gustilo–Anderson type IIIB case with a severe bone defect. By implanting bone cement and utilizing the 3D printing technology, we performed preoperative simulation, obtained a customized prosthesis to complete the individualized TEA, and proposed some improvements on the prosthesis design. The "informed consent" was obtained from the patient for publication of the case details and the accompanying images.

Case Presentation

Clinical Data

The patient, a 31-year-old male classified as Gustilo–Anderson IIIB, was injured in a traffic accident and suffered an open fracture of his left elbow. There was an open wound of about 10 cm deep into the bone. No obvious abnormality in blood supply and feeling was found at the end of the affected extremity, and the hand movement was severely limited. The preoperative X-ray and computed tomography (CT) imaging showed a severe bone defect in the humerus and ulna (Figure 1).

First-Stage Treatment

General anesthesia was induced in the supine position. The tourniquet and disinfection were routinely performed. The wound was enlarged appropriately along the longitudinal axis of left arm, a thorough debridement was given, and nerves and arteries were explored. There was no apparent injury of the ulnar and radial nerve during the operation. The bone defects of humerus lateral condyle and olecranon were found. At the same time, a PMMA spacer with antibiotic was shaped and inserted to reconstruct the humerus, and the end of triceps on olecranon was preliminarily reconstructed. An external fixator was used to provide stability (Figure 2). Finally, we used vacuum sealing drainage (VSD) to cover the wound, promote debridement, and heal the granulation tissue and wound.[18,19]

Second-Stage Treatment

Preoperative Design of Individual 3D Printed Prosthesis and Simulation

Considering the severity of open trauma, we removed the external fixator at the 8th week of the first-stage surgery, put the affected limb in a cast and encouraged the strength training of forearm muscles. In order to avoid the possibility of the pin infection on the prosthesis replacement, the second-stage surgery was performed after the pin path was completely healed at the 12th week. The patient's elbow movement was significantly restricted (Figure 3). The examination revealed no effusion and sinus tract on the wound, and the inflammatory indicators such as erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP) had returned to normal. Because of the irregular defect of the elbow joint, conventional prostheses were no longer applicable.

We were eager to restore the elbow to the same size and shape as the original portion and preserve as much bone as possible to facilitate prosthesis revision, so we obtained the CT of bilateral elbow with 1 mm slices. Firstly, the lossless CT images on the left were saved in DICOM format and uploaded to a software program (Mimics 19.0, Materialize company, Belgium), and the preliminary virtual 3D reconstruction model was obtained through threshold segmentation and region growth processing. The obtained model was refined and converted into STereolithography (STL) file. Similarly, after importing the CT image of the unaffected side, the Mirror function of Mimics was used to obtain the mirror file. At the same time, the mirror images data of the unaffected side and the affected side images data were imported into the computer-aided system software Unigraphics NX (UG, Siemens PLM software company, Germany) to obtain the individual prosthesis data by Boolean subtraction. The prosthesis entity was eventually manufactured by an orthopaedic instrument company (Chunlizhengda Medical Group, China), which is mainly made of standard Ti6A14V titanium alloy, and the bushing is made of high molecular weight polyethylene. Moreover, a reconstruction plate contoured in advance, designed to connect the prosthesis to the humerus, was added. Finally, the STL files of the left reconstructed model were uploaded to the Toenier 3D printer (SAS, Montbonnot, France) to acquire a solid 3D model made of nylon resin material (Figure 4).

Before the second-stage surgery, we used the accurately measured 3D printed implant and the solid 3D bone model

Fig. 1 X-ray (A) and 3D reconstructed imaging CT (B, C, D) of preoperative imaging of the left elbow

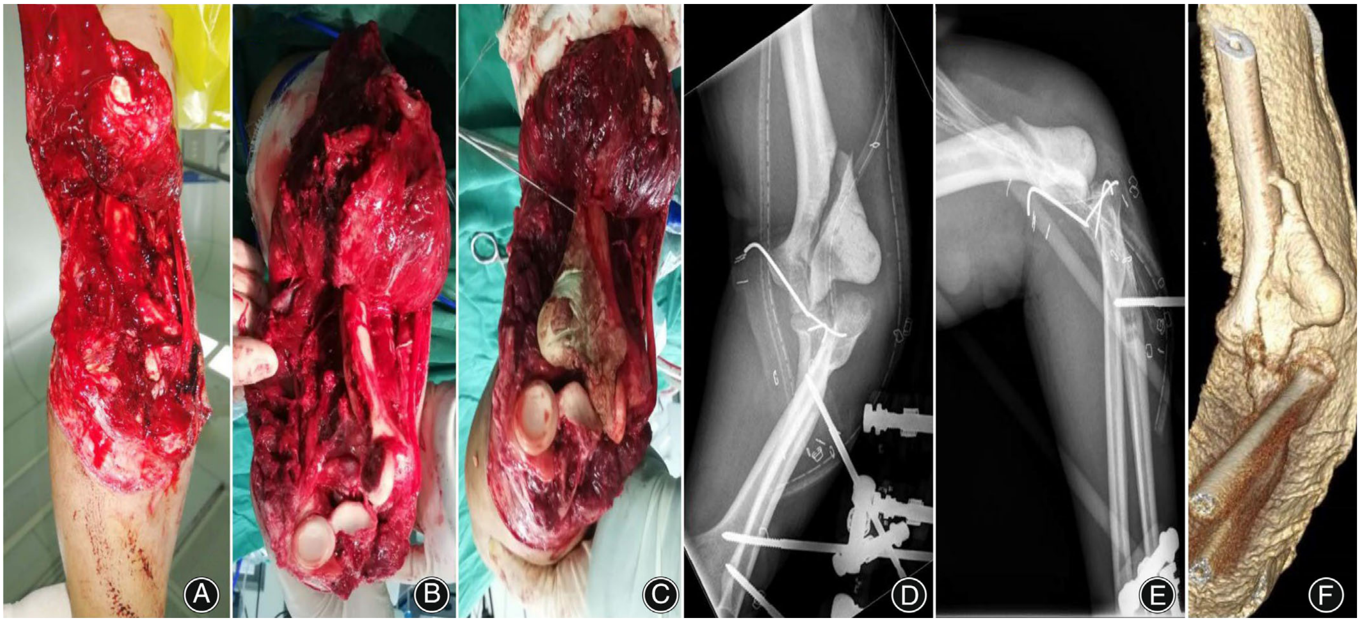

Fig. 2 (A, B, C) Photos taken during the first-stage surgery, showing a severe bone defect of the affected humerus and ulna. (D, E) Postoperative X-ray showed the bone cement and external fixation. (F) CT of the affected elbow in a cast

to simulate the operative procedure and adjust the size of the implant in time to make it more compatible (Figures 5 and 6).

Surgical Procedure
Intraoperatively, the patient was in a supine position. A posterior surgical approach was taken to expose the affected elbow, and the ulnar nerve was isolated.[16] Then the PMMA spacer was taken out. After determining the anatomical structure, a curette was used to remove the fibrous tissue and membrane inserted in the medullary cavity at both bone defeat extremities and the prosthesis contact surface, so that the vascularization was restarted. According to the preoperative simulation, the humerus osteotomy guide plate was installed and the wedge-shaped osteotomy was performed. The medial cortical bone was preserved. Intramedullary reaming of humerus and ulna were carried out. Subsequently, the prostheses were inserted into the medullary

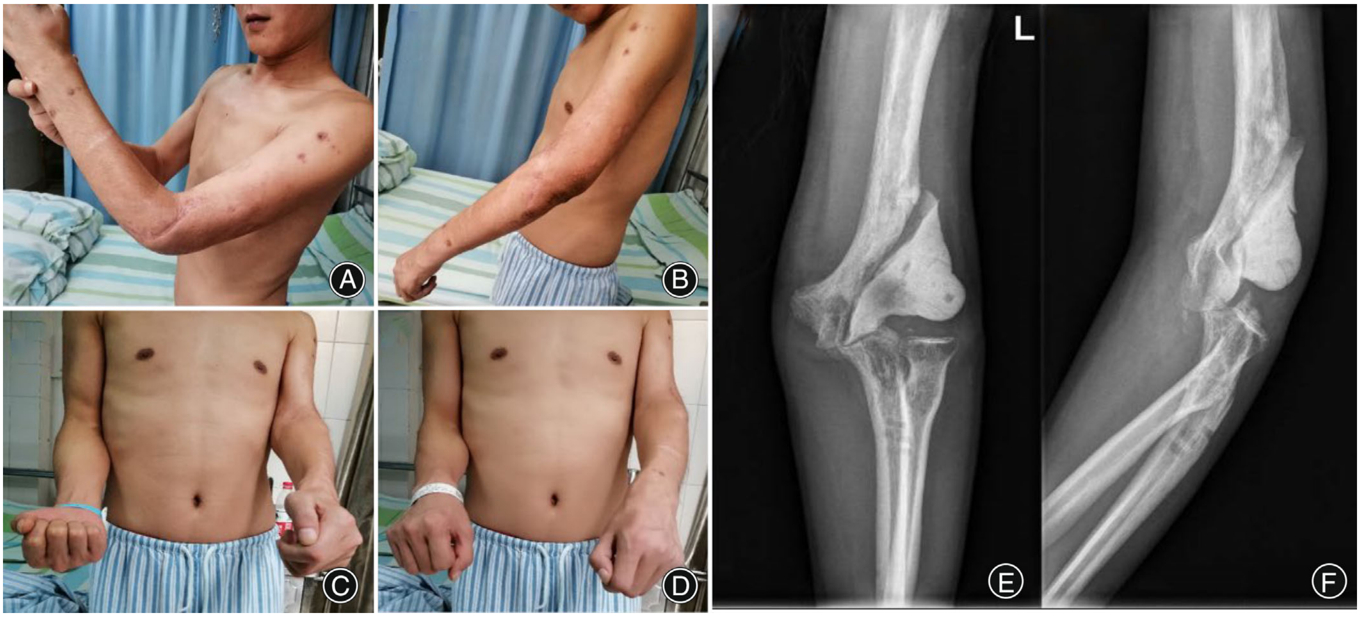

Fig. 3 Photos (A, B, C, D) and X-rays (E, F) of the left elbow joint before the second-stage surgery, showing the limitations of movement

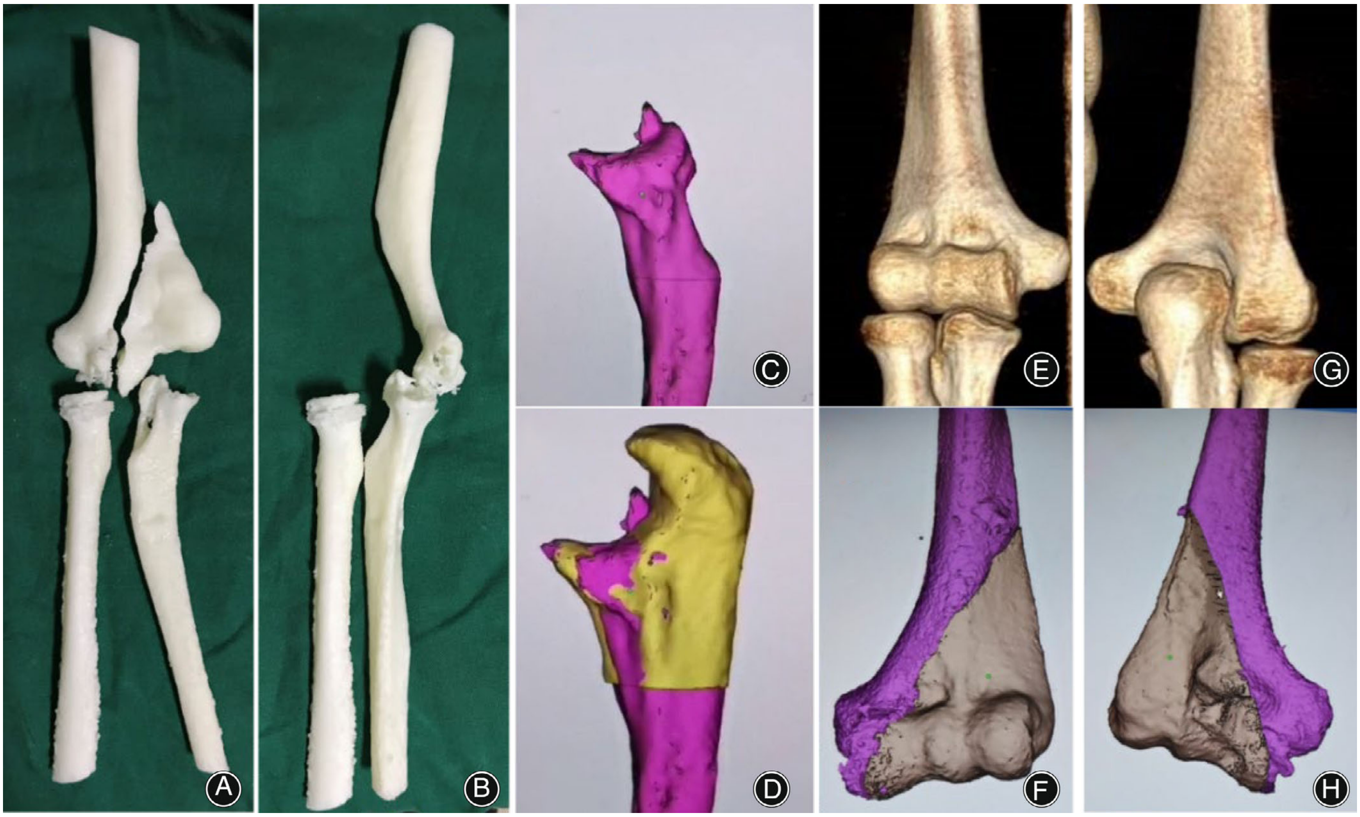

Fig. 4 Design and manufacture of prosthesis. (A, B) Printed bone model to evaluate the bone defects and plan surgical procedures. (C, D, E, F, G, H) Simulation of filling bone defects with mirror image technology

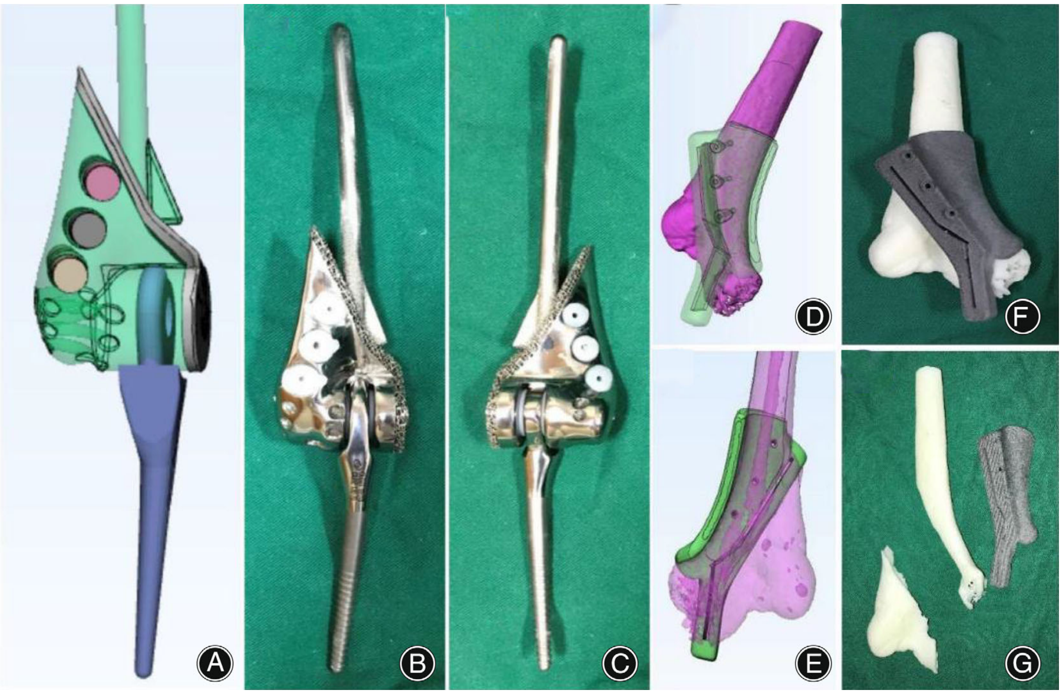

Fig. 5 Design (A) and photos (B, C) of the 3D printed prosthesis. (D, E, F, G) The design and photos of the osteotomy guide plate

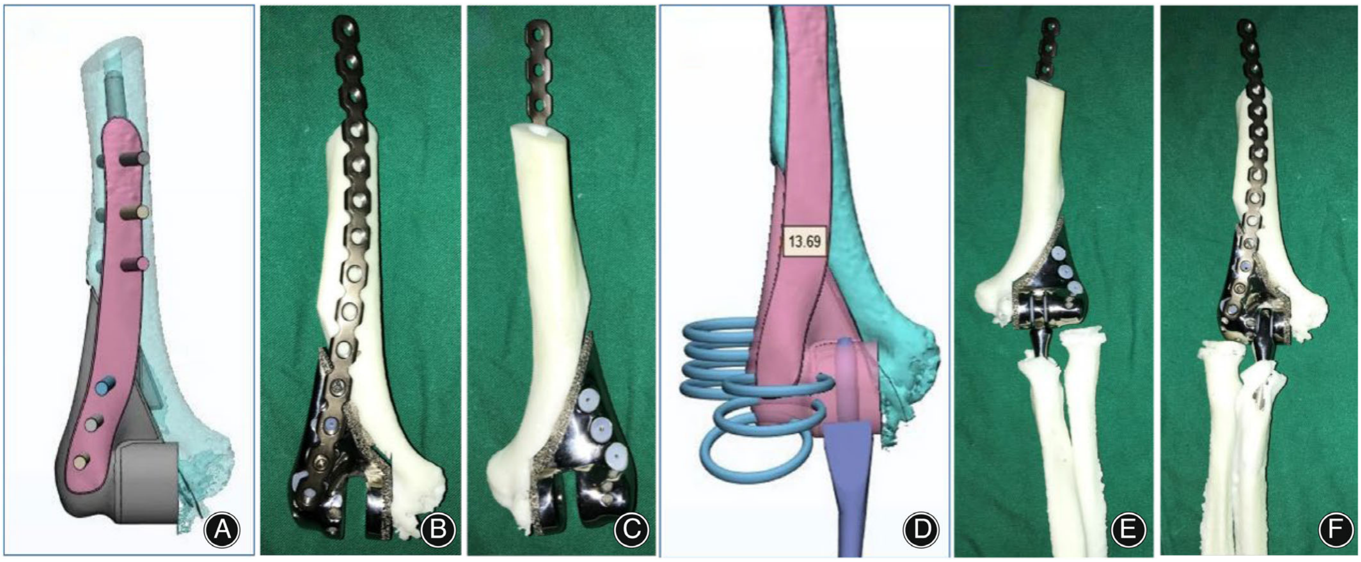

Fig. 6 (A, D) Computer-aided design of prosthesis. (B, C, E, F) Preoperative simulation of the 3D elbow prosthesis replacement

cavity. The left elbow bone defects perfectly matched with the individual customized 3D printed elbow prosthesis, and the anatomical reconstruction was performed satisfactorily. Then a pre-contoured reconstruction plate was implanted to consolidate the connection of the prosthesis and humerus. The stability of left elbow and implant placement were checked intraoperatively. The triceps tendon and collateral ligament were sutured, fixed on the prosthesis drill holes, and reinforced. Finally, the joint capsule was rinsed, and the incision was closed layer by layer. The postoperative X-ray

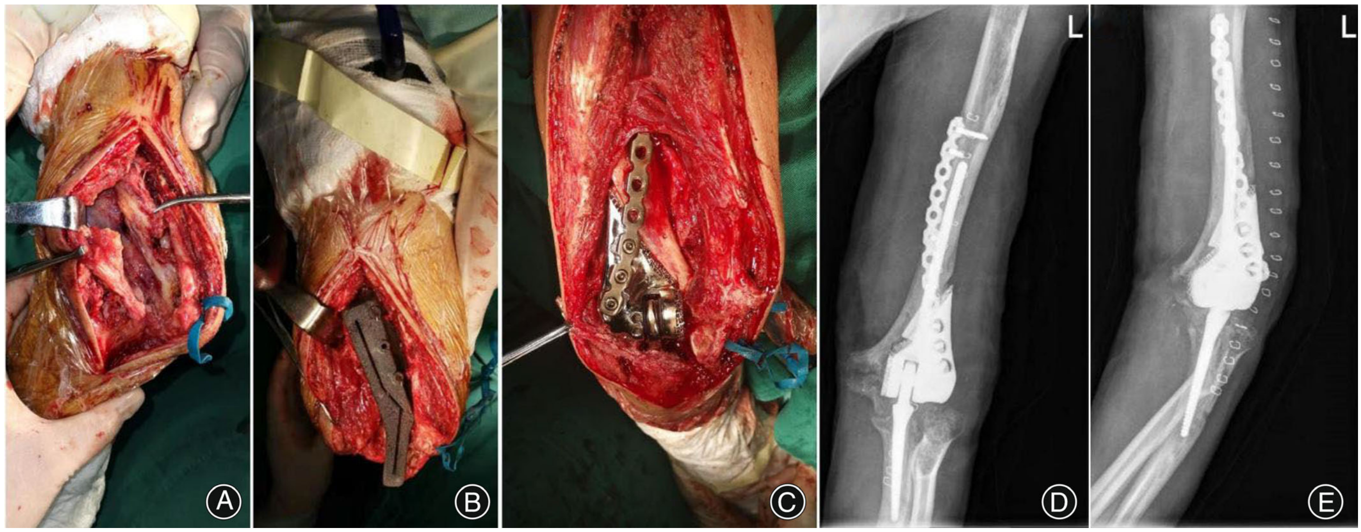

Fig. 7 Surgical procedure (A, B, C) and postoperative X-ray (D, E) for total elbow arthroplasty during the second-stage surgery

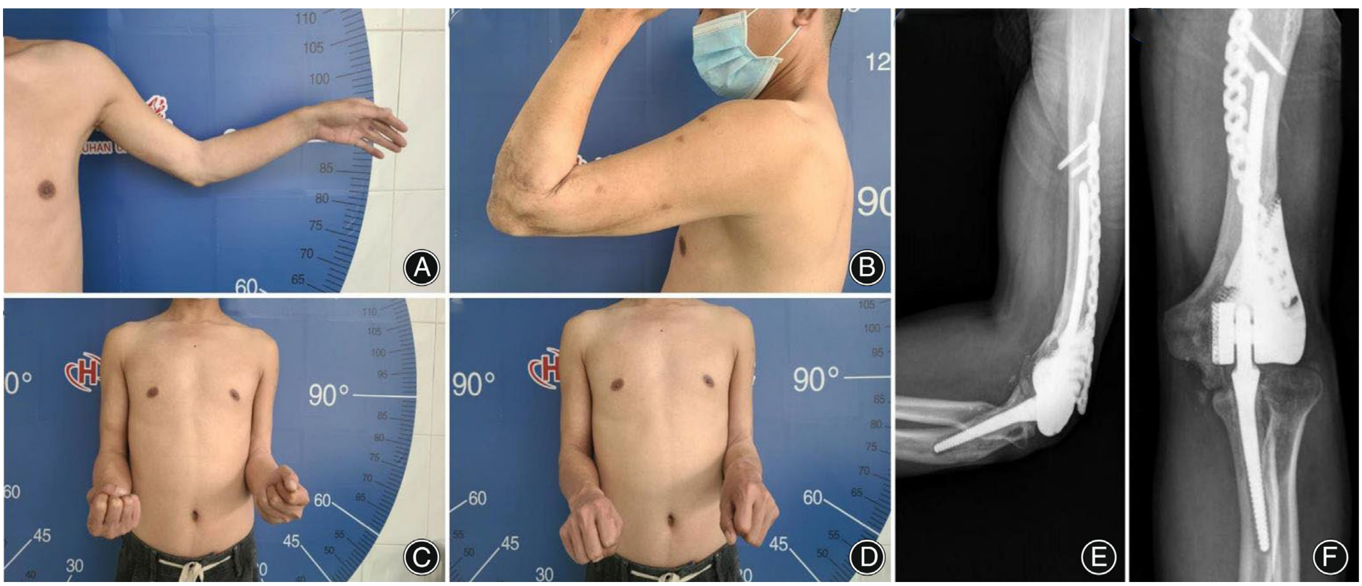

Fig. 8 Photos (A, B, C, D) and X-ray (E, F) after 15-month follow-up after the TEA surgery

showed that the prosthesis was in an accurate position (Figure 7).

Postoperative Follow-Up

Moderate exercise should be started on the second day post-operatively, and elbow flexion and extension exercises without weight-bearing were recommended 1 week later. Strengthening exercises began typically after 6 weeks. The patient returned for a routine assessment through clinical examination and radiographs by the treating physician. At the 15-month follow-up after the TEA surgery, the X-ray of left elbow showed the prosthesis in a good position, and the stability of prosthesis and plate was achieved. The function of the affected elbow joint recovered well (Figure 8). The Mayo score was 86. The elbow and forearm range of motion (ROM) was examined, elbow flexion 32°–125°, supination 45°, and pronation 70°. Until now no complications, such as infection, extensor mechanism dysfunction, and periprosthetic fracture, were found. The distal prosthesis is slightly loose due to the same stalk structure as the conventional prosthesis, which cannot be avoided with the increasing service life.

Discussion

Gustilo–Anderson III type open injury is defined as extensive soft tissue damage, periosteal stripping, bone exposure, and serious infection, where the increased risk of potential infection makes it more difficult to heal. Active prevention of infection is advocated, and open fractures are converted into closed fractures as soon as possible to achieve limb salvage.

In the emergency-stage of this case, the following strategies were adopted: First, the VSD dressings were placed to isolate the wound from the outside. Through continuous negative pressure suction, the tissue swelling was reduced, local circulation was improved, and the growth of granulation tissue was accelerated. And then, we boldly introduced the induced membrane technique. It could successfully control or eradicate bone infection and facilitate defect reconstruction. Its effectiveness for treating infectious bone defects in the lower extremity had been testified.[20] High-concentration antibiotics locally released from bone cement effectively interfere with bacterial colonization and bacterial membrane formation. At the same time, bone cement prevented bleeding from the medullary cavity and cancellous bone, and temporarily reconstructed bone configuration to prevent soft tissue contracture.[21]

Total elbow replacement was initially used in the elderly with advanced rheumatoid arthritis and was later expanded to osteoarthritis, traumatic arthritis, and severe distal humerus fractures.[22–25] Compared with ORIF, especially among elderly patients with comminuted and intra-articular distal humerus fractures, the TEA group achieved better postoperative functional outcomes.[26] Ray *et al.* recommended TEA as a last-ditch attempt and salvage procedure in some technically challenging fractures.[27] However, due to the lack of long-term data, the application of TEA to young people is still controversial.[28] Generally speaking, fractures in young people are often caused by violence, with poor soft tissue conditions, so the universal prosthesis may not be suitable. On the other hand, the common complications of elbow replacement are still inevitable, mainly including infection, prosthesis looseness, and fractures around prosthesis.

Nowadays, 3D printing has become more and more common in treating orthopedic diseases.[29,30] The actual situation of the affected limb is more intuitively displayed by the printed model, which is beneficial to formulate the surgical plan and tackle the difficulties exposed in preoperative simulation. All in all, the operating time, the frequency of fluoroscopic images, blood loss, and re-operation rates will be reduced greatly.[29,31,32] Some additional tools such as reconstruction plates and osteotomy guides can also be designed to improve the matching accuracy of the prosthesis.

Infection is an absolute contraindication to TEA, so controlling the infection plays an essential role. After the first stage of debridement and antibiotic bone cement implantation, it can be seen that the patient's infection index decreased gradually, and we even did not conduct the second debridement. Considering that the patient was only 30 years old, we started to get down to how to recover the elbow as perfectly as possible. Our research revealed irregular severe intra-articular bone defects of the humerus and ulna and damaged collateral ligaments, leading to elbow instability. Based on the image data of the healthy elbow, the structure of personalized prosthesis completely imitated the anatomical structure of humerus and ulna, such as the carrying angle and the humeral distal anteverted angulation, which could ensure the perfect contact and match between prosthesis and bone surface. Without excessive osteotomy, it could be inserted into the bone firmly, shortening the operation time, and preventing the aseptic loosening and the fractures around the prosthesis caused by excessive stress concentration in a specific area. Additionally, given the mild regional contracture on lateral humerus condyle, the prosthesis was intentionally shrunk. And we pre-designed drill holes on the prosthesis to repair the elbow collateral ligaments and extensor ligament to stabilize the elbow further.

Secondly, this 3D printed personalized elbow prosthesis simulates the basic structure of the Coonrad-Morrey prosthesis, which belongs to semi-constrained linked implants and limits the back extension. They permit some varus-valgus movement, and the laxity of the hinge structure is thought to reduce the incidence of aseptic loosening.[33] But prosthesis looseness and failure will occur in the later stage, so we take two measures to prevent it: (i) we used an additional plate contoured in advance to strengthen the connection between bone and prosthesis; (ii) on the contact surface between the prosthesis and the stump, we employed titanium mesh to facilitate the growth of bone. The 3D printed prosthesis is based on the semi-restricted joint design with a higher 5-year survival rate than the non-restricted elbow joint prosthesis in theory, as is the 10-years survival rate. We expect this prosthesis to serve for 10 years or more. Unfortunately, as we can see, the distal conventional prosthesis stem has become locally loose due to the patient's long postoperative writing work, but the proximal reinforced prosthesis has fused perfectly with the bone. The ulnar marrow cavity is thin and curved, making it difficult to fill with bone cement. And the ulnar stalk is also very thin, so the ulnar stalk of artificial prosthesis is usually not firmly fixed. Moreover, the contradiction between the forearm rotation movement and the limitation of prosthesis further increases the possibility of ulna stalk loosening. Therefore, a threaded structure and surface coating had been designed on the distal ulna stalk to enhance osseointegration in this patient. According to reports, the shorter handle would affect the rotation stability and cause looseness, so the length of the handle could be increased in subsequent improvements. Meanwhile, although the patient in this case did not fully return to normal elbow motion, the flexion angle was sufficient for his daily life. The patient had no further requirements, so we have not recommended the further treatment. This does not mean that the 3D techniques could not achieve perfect outcomes. We still have some improvements, such as prosthesis design, surgical operation and postoperative management, in the future work.

In a word, 3D printing technology offered the possibility of accurate reconstruction, satisfied the need for customized clinical applications, and simplified the complex procedure. However, our study had several limitations. Although the short-time follow-up outcome is satisfactory, long-term follow-up is needed. Second, the cost of operation using 3D printing technology and 3D printed prostheses is relatively expensive. Third, large sample research on the application of this technology is needed.

Conclusion

Modified Masquelet technique assisting 3D printed elbow prosthesis is an effective way for the treatment of open elbow fracture with severe bone defect as it can prevent and even eradicate the infection, anatomically rebuild bone defect, and improve the surgical outcomes. It can also be used for the similar surgery of open fracture of other joints.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

Author's Contribution

YL, YGR, ZY conceived and performed the surgery. ZCQ, ZC followed up the patient, collected and analyzed the data. All authors contributed to the manuscript and reviewed and approved the final submission.

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Authorship Declaration

The authors declare that they have no conflicts of interest in the submission of this manuscript, which is approved by all authors for publication. All authors listed meet the authorship criteria according to the latest guidelines of the International Committee of Medical Journal Editors.

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