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Three-dimensional printed bone cement prostheses can be used to treat bone defects in the distal humerus

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Complex distal humerus fractures with bone defects are still a great challenge in clinical treatment.[15] Elbow replacement is one option, especially for the elderly. But for young people, elbow replacements often fail to produce the expected results and carry the risk of requiring a second replacement.[4,9] Several reports have described bone defect reconstruction surgery using the Masquelet-induced membrane technique.[7,16,17] However, it is mainly used for segmental bone defects and has not been used for intra-articular bone defects.[2] Iliac crest grafting is a routine treatment for bone defects, but due to the special anatomical shape of the distal humerus, it is difficult to obtain the appropriate shape and size of the iliac crest. Custom-made metal implant may be a good choose, but it is expensive, difficult to manufacture, and require clinical approval. Cement has proven to be a safe and effective implant and has been used in the treatment of lumbar fractures, sternum reconstruction, and bone tumors.[10,18,19] It may also be a feasible, inexpensive, and readily available material for distal humeral defects.

Three-dimensional (3D) printing is an "additive manufacturing" technology based on digital signals.[12] With the continuous development of orthopedic digital precision treatment concepts, patients' requirements for joint function and limb appearance are constantly improving. How to completely repair the bone defect, restore the joint function of the limbs, and provide individualize treatment for each patient's condition has always been the most important issue of orthopedic surgeons.

In this case, bone cement was organically combined with 3D printing technology, and a more accurate personalized bone cement prosthesis (digital cement prosthesis) was designed according to the patient's condition. It proves that digital cement prosthesis can be used as a temporary solution or alternative to the treatment of traumatic bone defects.

Case report

A 20-year-old man presented to our emergency department after machine damage. He had an extensive avulsion injury from his upper left arm to his shoulder. X-rays and computed tomography (CT) showed a radial head fracture and a large bone defect in the distal humerus (Fig. 1). There was no neurovascular damage. The patient was previously healthy, no surgical history or medications available. Débridement and vacuum sealing drainage were performed immediately after the injury. In view of the extensive soft tissue avulsion and the intricate bone defect, we planned staged treatment that included soft tissue reconstruction and bone reconstruction.

Within 1 month after injury, the patient underwent multiple flap transfers and skin grafts in the burn department (Fig. 2). About 2 months after injury, there was no infection and the flap healed well. We were planning a bone reconstruction. Considering the patient's age, economic status, and risk of postoperative infection, we chose gentamicin-containing bone cement as the implant. Bone fragments of the radial head were removed intraoperatively.

According to the shape of the defect of the lateral humeral condyle, we designed the 3D printing personalized prosthesis

Institutional review board approval was not required for this case report.

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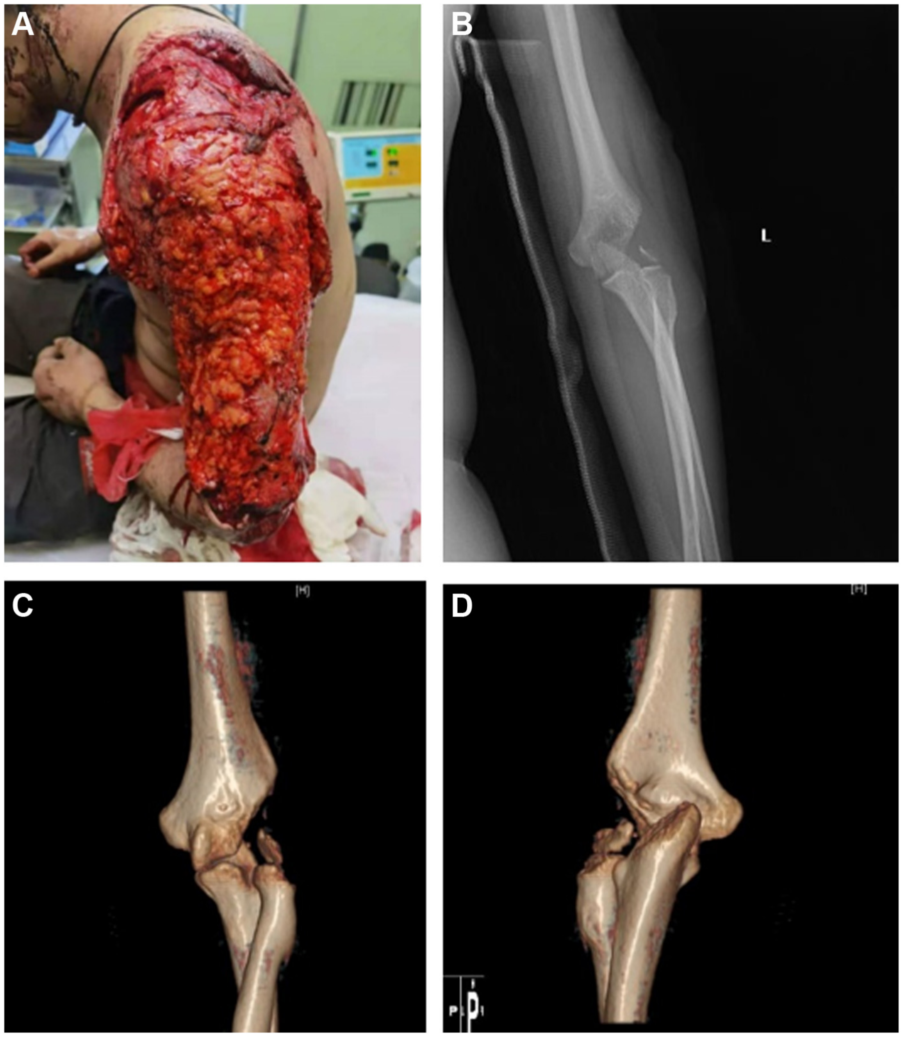

Figure 1 Images of a 20-year-old man who suffered an extensive avulsion injury and a large bone defect in the distal humerus. (**A**) An extensive avulsion injury from his upper left arm to his shoulder. (**B**) X-ray showed a large bone defect in the distal humerus. (**C, D**) Three-dimensional computed tomography showed a radial head fracture and a large bone defect in the distal humerus.

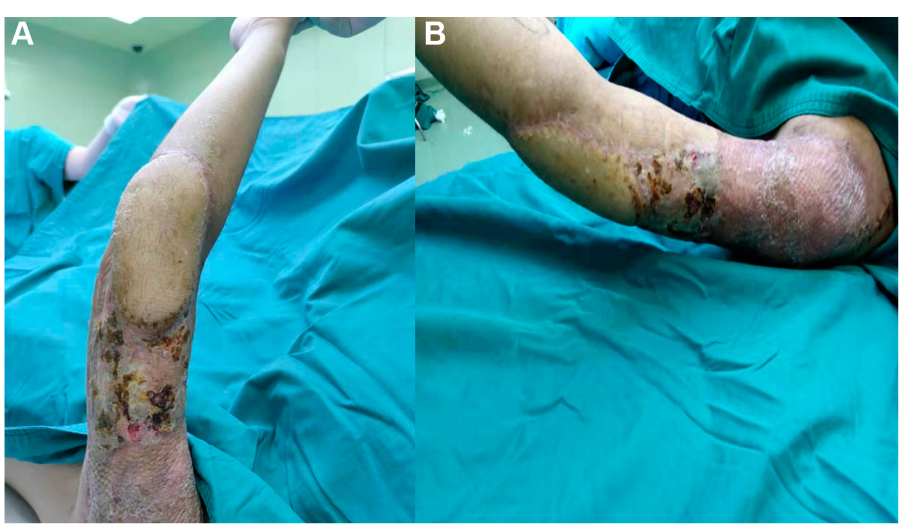

Figure 2 The patient's skin condition 2 months after injury. (**A, B**) Within 1 month after injury, the patient underwent multiple flap transfers and skin grafts in the burn department.

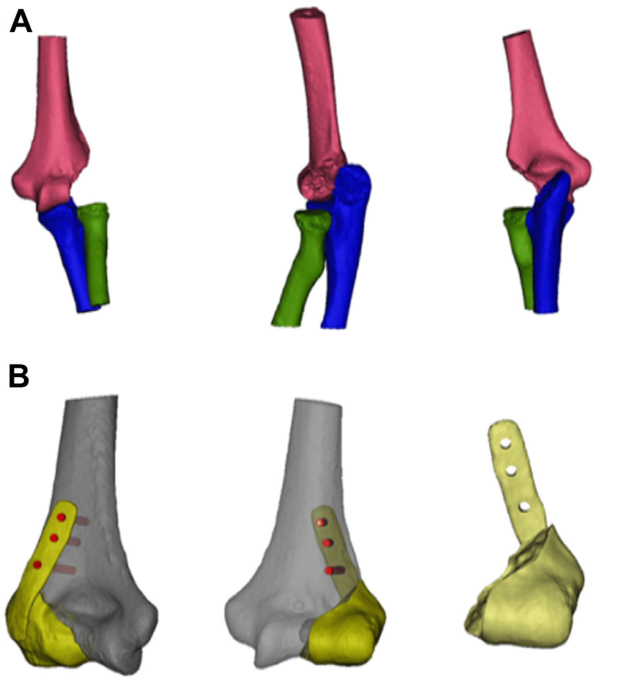

Figure 3 3D printing personalized prosthesis in the computer. (**A**) Imaging 3D reconstruction in Mimics21. (**B**) According to the shape of the defect of the lateral humeral condyle, 3D printing personalized prosthesis was designed. *3D*, three-dimensional.

(Fig. 3). 3D CT scans of bilateral elbow joints were performed using Light Speed 64-slice spiral CT (General Electric Company, Boston, MA, USA), with scan parameters: tube current 300 mA, voltage 120 kV, matrix 512 × 512, and slice thickness 1.0 mm. The thin-slice CT images were saved in DICOM format and imported into Mimics21 software (Materalise, Belgium) to obtain a 3D model of the distal humerus in STL format through noise reduction, threshold segmentation, mask editing, and 3D reconstruction operation process. The 3D distal humerus models were imported into Geomagic Wrap2017 software (3D Systems, Rock Hill, SC, USA), and the unaffected (right) distal humerus model was mirrored to restore the complete left distal humerus model. With the help of the best-fit alignment procedure, the affected humerus model was automatically fitted to the mirror model (Fig. 4, *A*). Due to the superiority of the right limb, we found that the mirrored model is slightly thicker than the left model during the design process. We imported the matched and aligned models into Freeform 2017 software (SensAble, USA), and used force feedback virtual sculpting technology and Boolean operations to obtain the defect lateral condyle model of the humerus, which is the later bone cement prosthesis (Fig. 4, *B*). In Freeform software, the surface of the "bone cement prosthesis model" was offset and thickened by 3 mm to get the cavity of the bone cement molder mold, and then the mold was divided into 2 parts to ensure that the mold can release the cement prosthesis smoothly (Fig. 4, *C*). The bone cement mold and the affected humerus model were 3D printed using the laser nylon dry powder sintering technology (Electro Optical Systems; EOS GmbH, Germany). The printed models and internal fixation instruments were sterilized under high temperature and high pressure before surgery (Fig. 4, *D*).

During the surgery, we poured the bone cement slurry into the mold, removed it from the mold before the bone cement was completely hardened, and placed it accurately on the 3D printed humerus model. Then we fixed the bone cement prosthesis and humerus model with bone plates and screws. The bone plate and bone cement prosthesis complex were removed from the model and then implanted into the human body together (Fig. 5). Intraoperative and postoperative imaging studies showed a perfect match between bone cement and the defect of the distal humerus (Fig. 6). Two month postoperatively, the patient had good elbow stability and was satisfied with the function and the Mayo score was good (80) (Fig. 7). Six month postoperatively, the patient's photo showed a better elbow range of motion (Fig. 8).

Discussion

Despite the increasing number of surgical techniques available today, there is still no consensus on the optimal treatment for complex distal humeral defects. In this case, we encountered a young patient with an extensive avulsion injury and a defect of the distal humerus. Such patients are rare in the world and rarely reported in the literature, which presents us with great challenges in treatment. The first thing we thought of was to do joint replacement directly, as elbow arthroplasty has proven to be an effective treatment for complex distal humeral fractures.[4,6] Considering the age of the patient and his own acceptance, we agreed that total elbow arthroplasty (TEA) was an excellent option in geriatric fractures with osteoporotic bone but should be not considered in this case. Iliac crest graft may be the option of many surgeons, but how to keep the articular surface flat and how to obtain the appropriate shape and size of the iliac crest was still a challenge that cannot be solved. Masquelet's technology has been popular in recent years. It has been reported for the treatment of segmental bone defects of the humerus, ulnar, and femur, but not for the indications of intra-articular bone defects.[7,16,17]

Given the limited studies available similar to our case, it is hard to determine which options are best for patients. Trung et al presented 2 clinical cases of megaprosthesis elbow replacement for treatment of bone defects caused by sequelae of trauma. They recommended that megaprosthesis elbow arthroplasty is an optimal option to help restore the anatomic and function of elbow joint in these cases of large bone defect and severe damaged joint caused by trauma sequelae.[20] But after surgery, there may still be risks such as infection, loosening of artificial joint, or nerve injury. Lee et al suggested that TEA shows a relatively higher failure rate compared to replacement arthroplasty for other joints, with a mean failure rate varying from 33% to 94% at 10 years. They introduced an autogenous fibular strut and iliac corticocancellous bone graft to reconstruct a large bone defect in revision TEA.[13] Kamalapathy et al[11] studied complications and survivorship of distal humeral allograft reconstruction after tumor resection. Complications from allograft reconstruction include infection, subluxation, fracture, and nonunion. Megaprostheses present similar complications in addition to aseptic or septic loosening. Based on their experience and the review of the literature, nonunions are the most frequent complication and junctional fractures are the most common cause of revision of allografts in this location. Alike et al[1] explored the feasibility of fabricating molds using a 3D printer for producing customized bone cement for repairing bone defect. They concluded that 3D printing customized bone cement shaping module can shorten the operation time, and customized bone cement prothesis has good match with bone interface, so it can avoid further adjustment and accord with the biomechanical rules of surgical site. But bone cement dislocation is a common complication after surgery, and the incidence of adjacent joint prosthesis dislocation has been reported as high as 38%. In general, it is not easy weighing the pros and cons of various options.

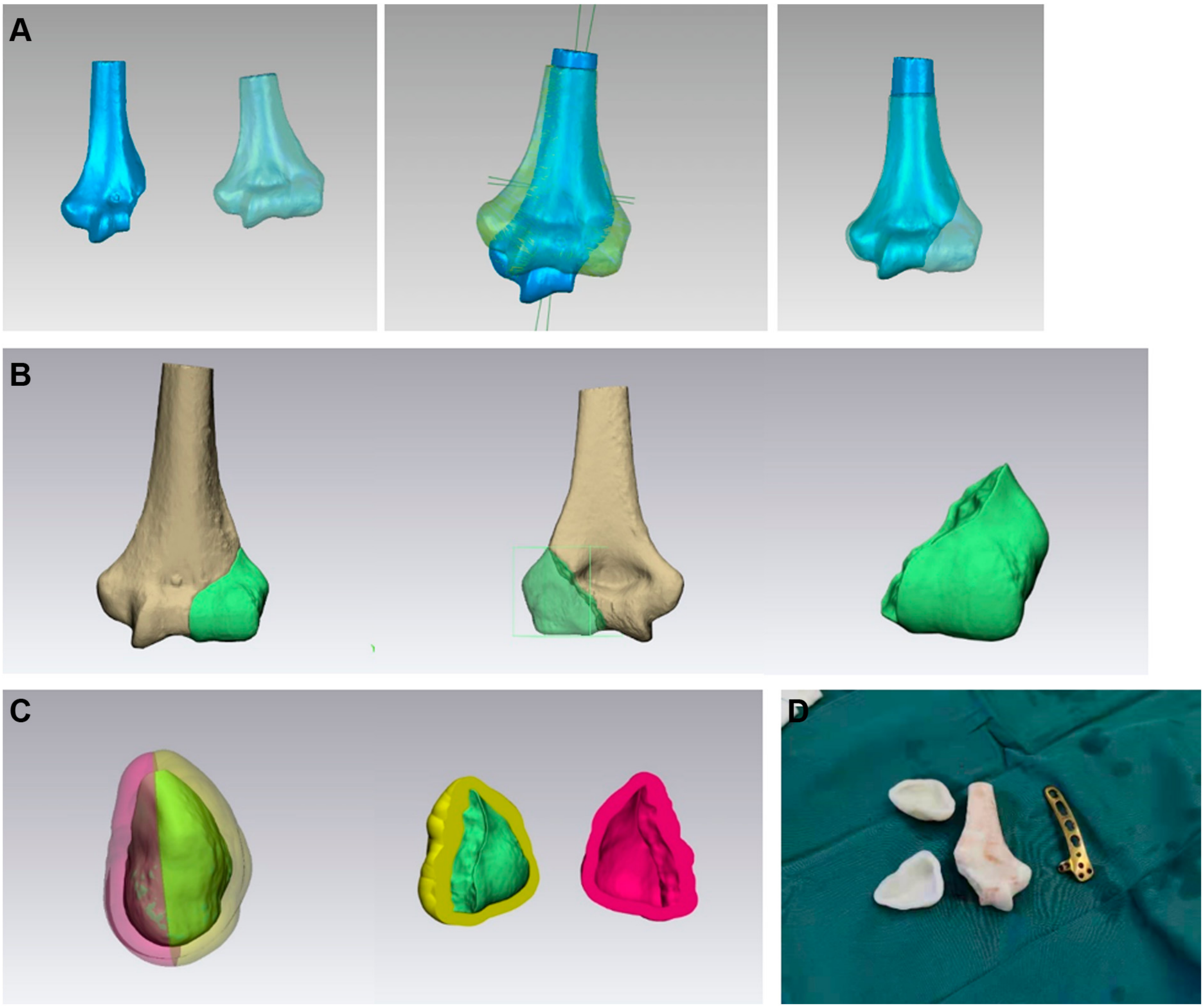

Figure 4 Bone cement molds are designed and printed using three-dimensional printing technology. (**A**) Mirror technology in computer programs. (**B**) Virtually engrave the prosthesis in the Freeform software. (**C**) Design and print bone cement shaping molds. (**D**) Sterilized bone cement molds, steel plates, and humerus models.

We ultimately chose cement as an implant for the distal humerus defect for several reasons. First, cement has been shown to be safe in the body and is most commonly used for lumbar spine compromises.[10,18,19] Second, since the patient had undergone multiple skin grafting operations, the risk of infection in the surgical area was high. The bone cement contained gentamicin, which could reduce the risk of infection. Third, cement is cheaper than custom-made metal implants, reducing the cost of failure. Finally and most importantly, we had a successful case with a similar patient who underwent cement graft filled the bone defects in the distal humerus last year.

3D printing technology has become the hottest emerging science and technology, while the rapid development of 3D printing technology has also played a role in promoting the development of digital medical treatment in orthopedics.[3,5] 3D printing–assisted orthopedic surgery technology is a milestone progress in digital personalized orthopedic treatment, and its emergence perfectly solves the problem of clinical personalized treatment. In previous successful case, cement in the shape of distal humerus bone defect was made by hand according to the surgeon's experience and perception. In this case, bone cement is organically combined with 3D printing technology, and a more accurate personalized bone cement prosthesis (digital cement prosthesis) is designed. The digital cement prosthesis can be perfectly matched with the bone cement as shown in Figure 6. Whether to put the bone cement prosthesis into the body first or to combine the bone cement prosthesis with the plate in vitro and then put it into the body was a question that we hesitated before surgery. If we put the bone cement prosthesis into the body first, the digital cement can be closely attached to the fractured end of the humerus, but it is hard to drill in the bone cement prosthesis and insert the screws because the bone cement dries and hardens quickly. The high temperature of the drill may cause tissue damage. Fragments of bone cement may remain in the body. If we combine the bone cement prosthesis with the plate in vitro first, we will have enough time to insert screws in vitro. After the bone cement solidified, the bone plate and bone cement prosthesis complex were removed from the model and then implanted into the human body together, but the digital cement cannot be closely attached to the fractured end of the humerus. Considering the possibility of removing internal fixation for postoperative

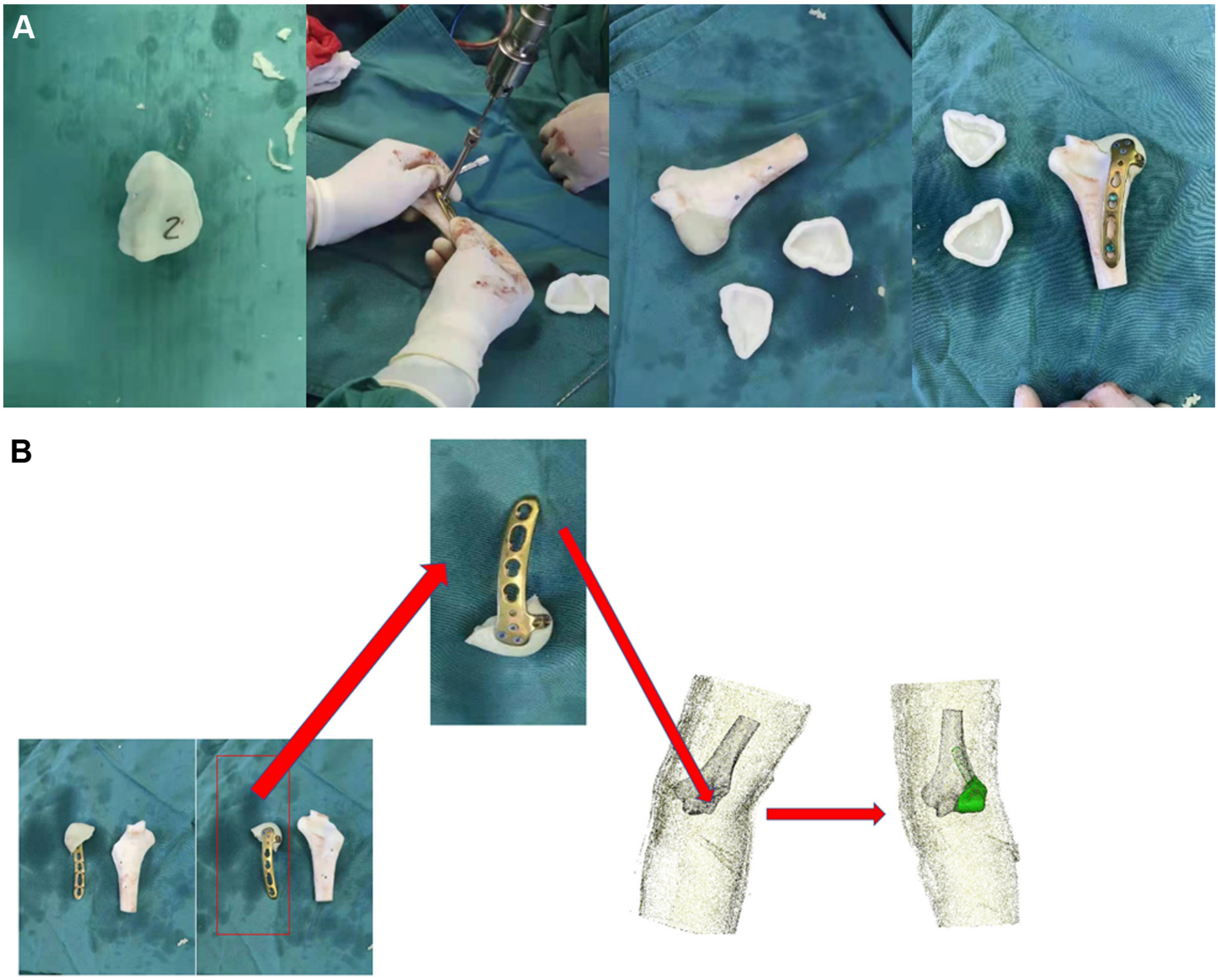

Figure 5 Display of surgical procedure. (**A**) Bone cement prosthesis making and plate fixed in vitro. (**B**) The bone plate and bone cement prosthesis complex were removed from the model and then implanted into the human body together.

infection, we chose the latter. If we choose the former, the cement implant may be difficult to remove because it is firmly attached to the humerus. In fact, the patient's wound did not heal for a long time after surgery. We performed a second débridement in the 20 days after the cement prosthesis implant, but no significant necrotic tissue was found during surgery, and no obvious infection was found in bacterial culture. However, the local wound of the patient was difficult to heal and secreted yellow fluid. We noted that the flap had poor blood supply and the patient's defective joint capsule could not protect the outflow of joint fluid (yellow secretion), which affected wound healing. Through immobilization and elevation of the patient's affected limb, and active dressing change, the patient's wound eventually healed. Due to delayed wound healing, the patient did not gain early functional exercise. Active functional exercise began after the wound was healed. Two months after surgery, the patient had good elbow stability and was satisfied with elbow function. The patient cannot come to our hospital for review on time due to COVID-19. Six months after surgery, his photos sent to us on-line showed a better range of motion and no loosening of the prosthesis or pain.

Despite the temporary good result, there are still many problems in this case. First, it is still unclear how long the digital cement prosthesis can be used. Second, the insertion point of the lateral collateral ligament was detached from the lateral condyle, and the bony structure of the lateral condyle was reconstructed, but the lateral collateral ligament could not be reconstructed. In the treatment of complex elbow fractures, the current consensus is that the lateral collateral ligament needs reconstruction and plays an important role in the stability of the elbow.[8,14] Interestingly, in this case, we did not reconstruct the lateral collateral ligament, but the patient had excellent lateral stability of the elbow. Third, we are still worried about the screw loosening wear and tear of bone cement, and whether there could be long term infection. We hope that these problems can be solved through follow-up and surgical technique advances. And we believe that more perfect therapeutic strategies will be developed to treat distal humeral defects in the future, such as infection-resistant custom metal implants and tissue engineering bioprosthesis. We hope that 3D printing technology will further develop to realize individualized treatment, widely used in clinical treatment, and benefit the patients.

Conclusion

TEA may not be the best option for young people who have suffered a complex elbow injury. Despite the potential risk of prosthesis loosening, 3D printed bone cement prostheses can be

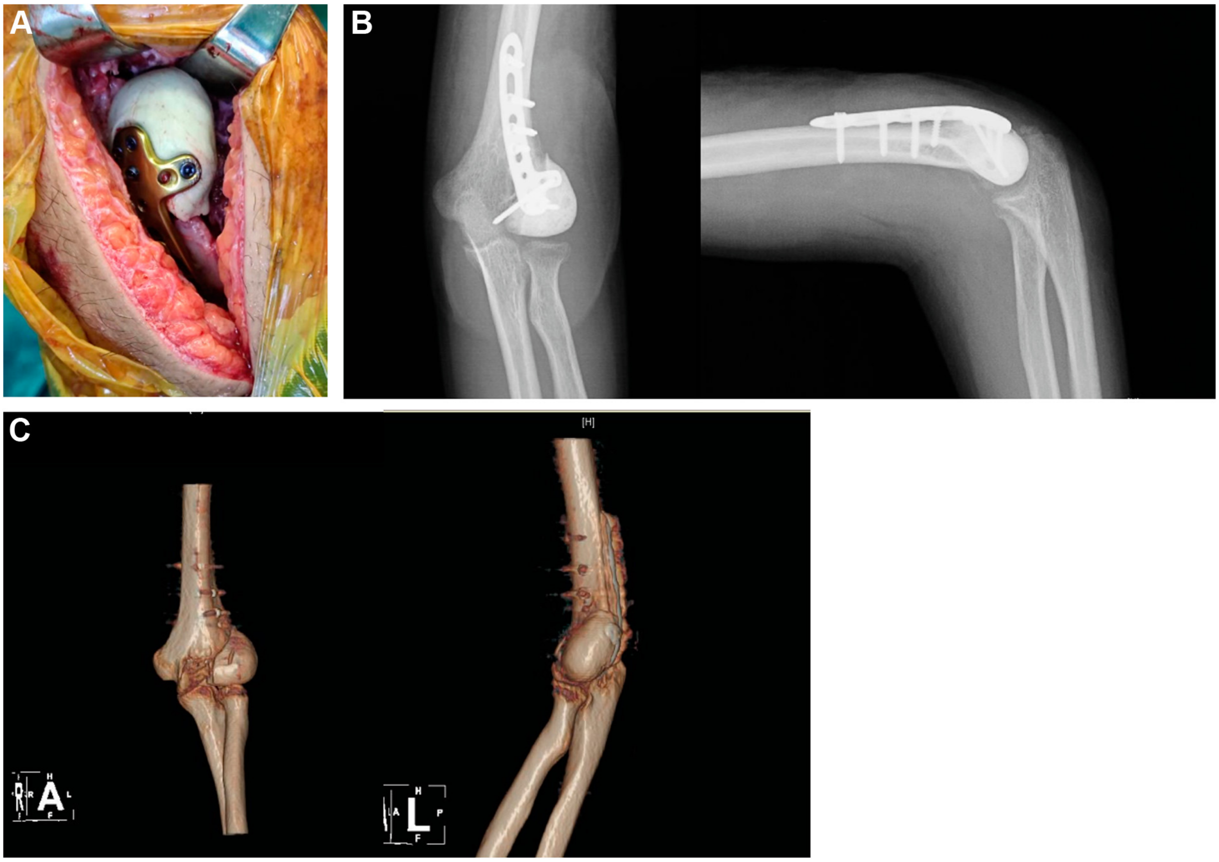

Figure 6 Intraoperative and postoperative images. (**A**) Image after placing the plate. (**B, C**) X-ray and 3-dimensional computed tomography after the surgery.

Figure 7 Photos of the patient 2 months after surgery. (**A, B**) The degree of extension and flexion is partially limited. (**C, D, E**) The degree of external rotation is limited.

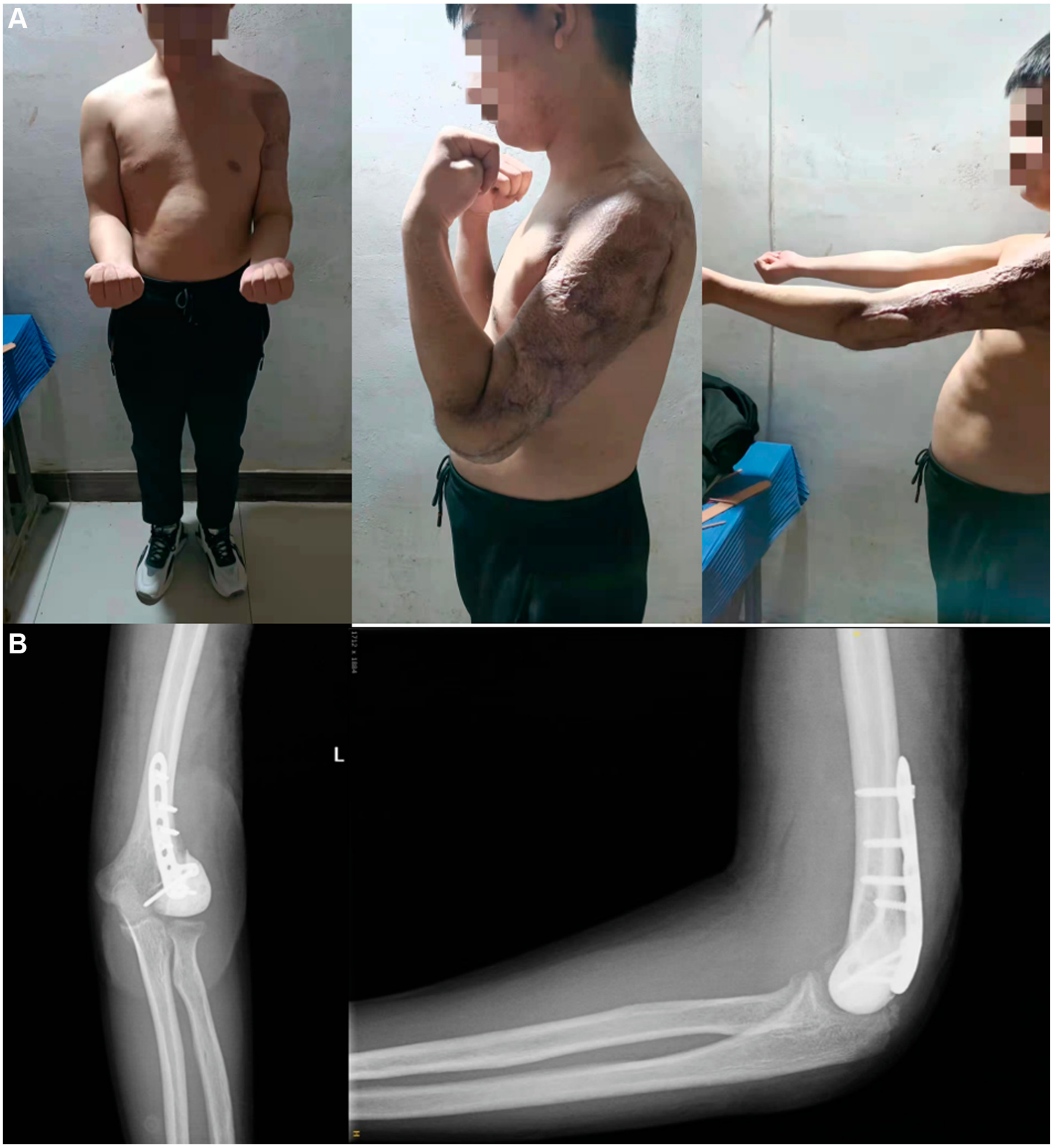

Figure 8 Photos and X-ray of the patient 6 months after surgery. (**A**) The degree of extension and flexion is slightly limited. The degree of external rotation is close to normal. (**B**) No prosthesis or screw loosening according to the X-ray.

used as a temporary solution or alternative to the treatment of traumatic bone defects in the distal humerus.

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