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New finger reconstruction technologies using 3D printing

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Abstract

Introduction The use of 3D printing technology in finger reconstruction improves accuracy of the procedure minimizing the donor defect and optimizing the appearance and function of the finger. The use of this technology in the finger reconstruction with an osteocutaneous radial forearm flap with axial blood supply and lengthening of the digital stumps and metacarpals remains poorly explored.

The objective of the study was to demonstrate new methods of preoperative planning for finger reconstruction and improve surgical outcomes.

Material and methods Outcomes of five patients treated with original methods based on 3D technology were retrospectively evaluated during preoperative planning, reconstruction of the thumb using an osteocutaneous radial forearm flap with axial blood supply, relocation of the stump of the third finger and lengthening of the stumps of the first and second metacarpals. The patients could achieve consolidation of interpositional bone allografts following lengthening of the finger stumps, stability of the bone base of the finger, organotypic restructuring of the marginal allograft during plastic surgery with an osteocutaneous radial forearm flap, and a functional position of the reconstructed thumb using the middle finger stump.

Results and discussion An individual device for planning finger reconstruction allows identification of the optimal size and position of the finger in three planes, which is essential for patients with severe hand deformities to avoid corrective procedures. An individual guide was used to osteotomize the radius to harvest a vascularized graft providing a cutout of a given size and shape and a cortical-cancellous allograft being identical in shape and size to replace the donor bone defect. The combined use of Masquelet technology and distraction of the finger stump or a metacarpal improved conditions for consolidation and restructuring of the interpositional allograft preventing fractures and infection.

Conclusion The use of 3D technology in finger reconstruction using an osteocutaneous radial forearm flap with axial blood supply and distraction of the finger stumps and metacarpals can improve surgical outcomes.

Keywords: Ilizarov method, Masquelet technique, 3D printing, finger stump, osteocutaneous radial forearm flap

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INTRODUCTION

3D printing technology has been developed in medicine over the past decade to be used in various medical applications; it offers promising opportunities to improve learning outcomes, surgical training and an individual treatment approach enhancing the efficiency of outcomes [1–3]. In surgery, 3D printing can be used to create geometrically complex and highly detailed personalized constructs and the one-time production, for preoperative planning, design of orthopaedic products and prosthetses in accordance with the specific requirements of the surgeon and patient [3–6], to create auxiliary devices, adapted for a specific patient, for intraoperative use, hardware and custom-made devices, implantable prostheses, rapid prototyping of surgically implanted products and training applications [7–10]. The advantage of the technology is that individual implants and casts can be made in accordance with the anatomy of a particular person [9, 11]. However, there is a paucity of studies reporting the use of the technology in hand surgery. There are few publications in the literature on the use of technology in toe transplantation and replacement of the donor defect with flaps by microvascular anastomoses. The technique helps to reduce operating time providing digital and accurate circuit diagrams to complete the operation. The authors created a model of the big toe and the second toe to understand the extent of tissue to be harvested from the donor site. This model was also applied to repair the donor site defect by using appropriate superficial circumflex iliac artery (SCIA)-based iliac skin-bone flap [9]. Preoperative planning for hallux reconstructions with second toe transfer using 3D printing was reported. Computed tomography angiography (CT angiography) is used to map the vasculature of the donor site, while CT findings are used to create three-dimensional models of the soft tissue and skeleton of injured and intact arms. Based on the reformatted model (a mirror of an intact hand), models of the soft tissues and skeleton of the fingers were created using a 3D printer. The toe model was also used to determine the level of osteotomy on the donor foot. This allowed optimization of the function and appearance of the reconstructed thumb minimizing injury to the donor site [12, 13]. The method can accurately calculate the skin and bone dimensions of the donor site as a reference for surgery and perform the operation according to the model [14]. The technology is also used to simulate the size of a skin-fat flap to replace soft tissue defects of a finger in emergency cases [15] and during hand transplantation [16]. Possibilities with 3D technology in other methods of finger reconstruction have not been explored. Different aspects of pre- and intraoperative use of 3D technology in skin-osseous reconstruction of the fingers and lengthening of the digital stumps and metacarpals are aimed at optimizing preoperative planning and precision of the procedure improving results, reducing the donor defect and the complication rate.

The purpose of the work was to demonstrate new methods of preoperative planning and reconstruction of fingers improving surgical outcomes.

MATERIAL AND METHODS

We retrospectively evaluated results of skin-osseous reconstruction with a radial flap of the first finger in two patients, lengthening of the stumps of the first and second metacarpals in two patients and relocation of the stump of the third finger in one patient using the technologies devised. Reconstruction of the first finger was scheduled using the device developed for both patients.

Technical performance

RF patent 211603 “Device for preoperative planning for reconstruction of the first finger” [17].

A device for preoperative planning for the finger was created using hybrid parametric modeling, topological optimization and additive 3D printing technologies. It was equipped with a socket for the finger stump, fixed on the hand with Velcro tape or adhesive tape with the distal part of the socket being connected with a ball joint with the ability to be fixed in a certain position with a sleeve connected to the piston with the ability to extend and fix the position achieved with a threaded rod, followed by measuring the finger length being restored and the angles of the fixation to the stump of the first finger (Fig. 1, a, b).

RF patent 2747694 “Method of skin-osseous reconstruction of a finger and a guide for its implementation” [18].

An individual model of the radius was created based on computed tomography and then, using this model, a guide was created for harvesting the graft at the donor bone site (Fig. 2). The guide for skin-bone reconstruction of the finger contained a groove for a saw blade and a central axial hole; it was manufactured individually according to computed tomography data using 3D printing, depending on the intended size and shape of the graft. The length of the guide at the distal end was at least 1 cm longer than the intended graft, and the length at the proximal end was at least 2.5 cm. The device consisted of two equal palmar and dorsal parts. The axial hole precisely corresponded to the lateral surface of the radius at the site of the planned graft. The groove for the saw blade was shaped as a scaphoid; in the middle, at the distal end of the guide, a continuous slot 2 mm wide was made to accommodate the intermuscular septum and the vessels. A “protrusion-groove” connecting component and two holes for the pins were secured proximally (Fig. 2, a, b).

RF patent 2796438 “Method of distraction lengthening of the metacarpal stump” [19].

An osteotomy site and the required dimensions of the distracted distal fragment of the metacarpal and the cross section at the level of osteotomy were determined with computed tomography of the hand at the stage of preoperative planning. Then, a hollow cylindrical spacer model was formed using hybrid parametric modeling (Fig. 3). The length and inner diameter of the spacer were measured depending on the distraction intended. The internal cross-section of the spacer corresponded to the cross-section of the distracted metacarpal at a distance of 0.5 cm from the site of the intended transverse osteotomy. The spacer had a semi-open through longitudinal rectangular groove 2 mm wide. The end edge of the groove ended at a distance of 0.5 cm from the opposite edge of the 1.5 cm long spacer. The ends of the spacer should be inserted to a depth of 0.5 cm on the ends of the proximal and distal bone fragments and considering the diastasis of the bone fragments by 0.5 cm. A matrix was created using 3D printing technology based on the spacer manufactured from PLA polymer material. The matrix was intraoperatively filled with bone cement containing gentamicin. The spacer was removed with the bone cement being hardened. A transverse osteotomy of the metacarpal was performed in the middle third using an oscillatory saw. The bone cement spacer was placed with a solid end on the proximal end of the distal fragment of the metacarpal. A Kirschner wire was placed intramedullary through the distal fragment of the metacarpal and the axial hole of the spacer. The proximal end of the wire was U-shaped with the short branch of the wire being inserted into the groove of the spacer until the bend area stopped at the end edge of the closed part of the groove and the proximal end of the distal fragment. The distal end of the wire was pulled out. The second end of the spacer with a groove was placed on the proximal fragment of the metacarpal. The Ilizarov frame with a reference ring was mounted to the forearm with screw rods attached. The distal end of the intramedullary wire was fixed to the screw rods. The postoperative wound was sutured. Gradual distraction of the distal fragment was performed at 5 days at a rate of 1 mm per day along with the cement spacer. The second stage of the operation was performed with distraction of the distal metacarpal fragment completed. In this case, the resulting osteogenic membrane was dissected along the entire length of the distraction defect and the ends of the metacarpal fragments. The intramedullary wire and spacer were removed, preserving the distraction regenerate.

The distraction defect was repaired with a cortical-spongy allograft with the transverse dimensions not exceeding the outer diameter of the spacer. The resulting distraction regenerates at the distal and proximal fragments of the metacarpal were preserved. Osteosynthesis of bone fragments and graft was performed with wires. The resulting osteogenic capsule was sutured with interrupted absorbable sutures over the graft and the contact area of the metacarpal fragments. The subcutaneous tissue and skin over the osteogenic capsule were sutured in layers.

RESULTS

Case report

A 45-year-old patient Ch. was admitted to the PIMU hospital for a severe mechanical injury resulting in a stump of the first finger at the level of the metacarpal head, severe adduction contractures of the first metacarpal bone, stump of the third finger and deformity of the fourth finger, flexion contractures of the second finger in the interphalangeal joints, intra-articular comminuted fracture the head of the main phalanx, ulnar deviation of the middle phalanx of the fourth finger on the right side (Fig. 1, c). The patient wanted to restore pinch grip I with preserved finger II. The patient presented with sharply limited functionality of the hand on admission with no grip, 15–20° range of motion in the metacarpophalangeal, interphalangeal joints of the second finger and the carpometacarpal joint of the stump of the first metacarpal bone. The length of the stump of the first finger was 5.5 cm. The patient refused a toe transplant and skin-osseous reconstruction of the first finger with the radial flap. The reconstruction of the first finger included transfer of the stump of the third finger due to the lack of the grip function. Limited function of the second finger and poor opportunities for the improvement, adduction contracture of the first metacarpal necessitated measurements of the adequate length and position of the reconstructed first finger. A computed tomography scan of the injured hand was performed preoperatively with established clinical and radiological diagnosis. Then a tailored made device was developed to measure the size and position of the reconstructed finger depending on the size of the stump of the third finger using hybrid parametric modeling, topological optimization and additive 3D printing technologies. The device was used to measure the length of the reconstructed finger and position in three planes. The size of the sleeve corresponded to the dimensions of the stump of the third finger being transferred. The device was fixed to the stump of the first finger using Velcro adhesive tape passed through the eyelets of the socket. The patient underwent functional testing of the hand was produced by gripping small-, medium- and large-sized objects using a device fixed to the stump of the first finger. The position and length of the reconstructed finger were empirically measured by gradual extension and fixation of the piston using the nut of the threaded rod and by changing the position of the sleeve together with the piston in three planes with fixing the hinge with a stopper ensuring the possibility of performing a pinch grip with a deformed second finger. The patient's professional requirements for the restored grip function were also considered. The length of the first finger and its position in the frontal, sagittal and horizontal planes were measured. The finger length was 6.5 cm measured from the base of the bushing to the distal end of the piston. The angle of radial abduction, palmar abduction, and rotation of the sleeve together with the piston were measured using an angle ruler. The magnitude of palmar abduction was 45°, radial abduction was 35°, and rotation of the sleeve with the piston was 90°. These parameters corresponded to the position and length of the stump of the third finger being transferred to the position of the first finger. According to measurements, the length of the finger being formed together with the metacarpal bone should have been 11.5 cm (the length of the first finger of the healthy hand together with the metacarpal bone was 10 cm). Dimensions and fixation angles of the stump transferred were used intraoperatively to transfer the stump of the third finger and fix it to the stump of the first metacarpal bone. A pinch grip of the reconstructed first finger with the stump of the middle phalanx of the second finger, with the fourth and fifth finger was achieved. There was no need to perform corrective operations to change the position of the first finger after the surgery. The patient could adapt to the new grip of the hand, hold small- and medium-sized objects using the I and II fingers, could hold large objects using the I and preserved IV, V fingers and use the reconstructed finger in everyday life and manufacturing activities. The distance between the first and second fingers with maximum abduction of the reconstructed finger and extension of the second finger measured 7 cm and 12 cm in the normal side. Abduction of the first finger and the adduction of the first to the second finger was restored (Fig. 1, c, d, e).

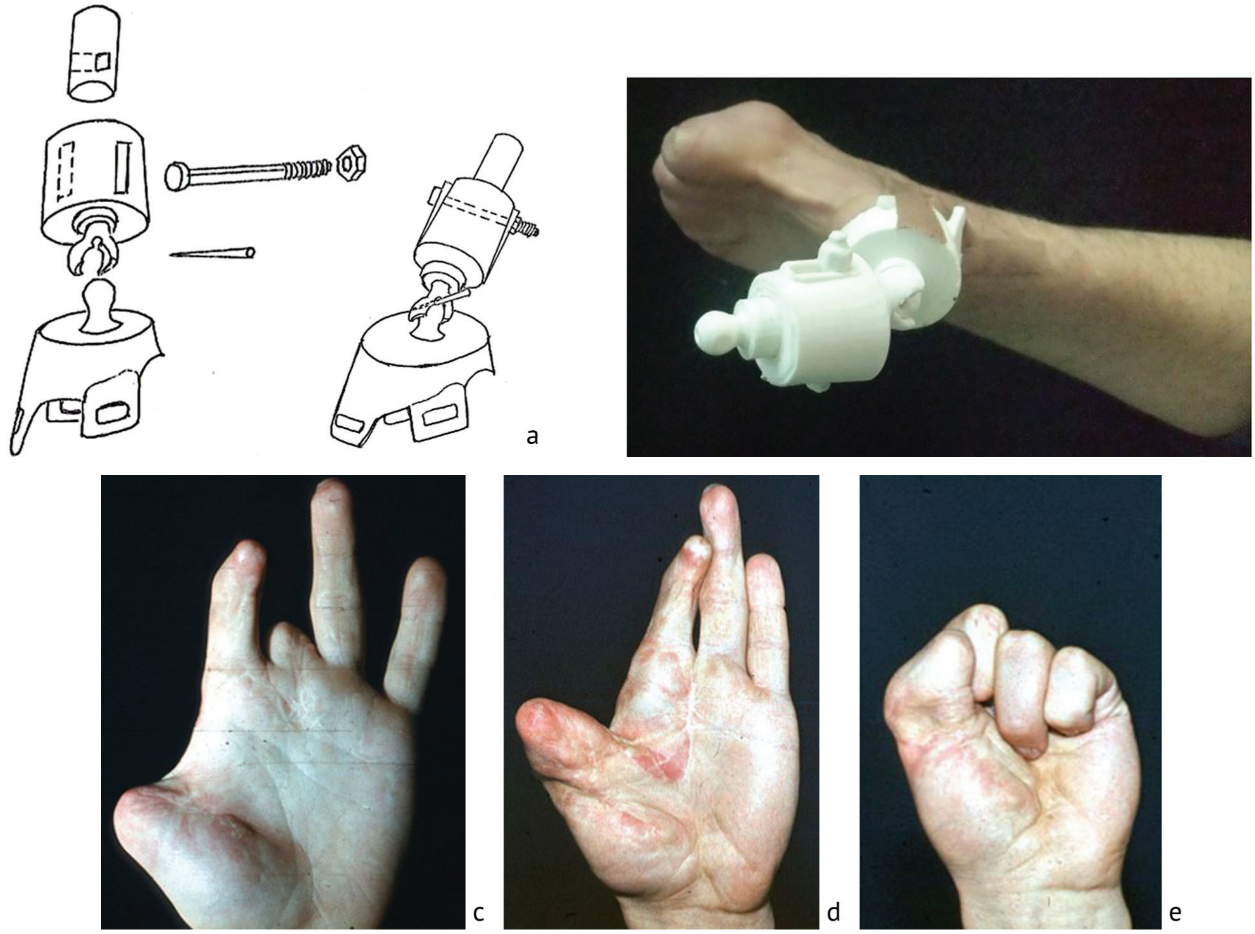


Fig. 1 A device for preoperative planning of reconstruction of the first finger: (*a*) components and the assembly; (*b*) the device fixed to the stump of the first finger; (*c*) preoperative appearance of the hand; (d) abduction function of the first finger; (*d*) double-sided grip function

A 25-year-old patient S. was treated at the PIMU hospital for the stump of the first finger on the left side at the base of the main phalanx, a soft tissue defect of the radial edge of the hand (Fig. 2, g). The patient sustained an industrial injury on 07/06/19 when her left hand got trapped by a processing machine. Soft tissue reconstruction of the first finger was produced for the patient and the soft tissue defect on the hand was repaired with plastic surgery using a non-free inguinal axial skin-fat flap (13/06/19). On 10/02/20, skin-osseous reconstruction of the first finger on the left side was performed by transfer of a skin-bone radial flap using a peripheral vascular pedicle. The required dimensions of the bone frame, the size and shape of the radial bone graft, the length of its vascular pedicle were preoperatively measured for the reconstructed finger and a computed tomography scan of the forearm performed. Then a tailored radial osteotomy guide was manufactured using hybrid parametric modeling, topological optimization and additive 3D printing technologies. The radial artery with a skin-fat flap was intraoperatively mobilized preserving the intermuscular septum with septal and periosteal vessels at the site of grafting. Two parts of the guide were applied to the osteotomy site and connected to each other. Then the guide, as a single block, was temporarily fixed to the site of the radial bone grafting using wires (Fig. 2, c). In this case, the intermuscular septum with septal vessels was placed in a continuous slot of the guide to prevent the injury with the radial artery being located laterally. A marginal scaphoid osteotomy of the radius was performed using a guide. The blade was pressed against the groove of the guide driving the saw. Integrity of the septal and periosteal vessels extending from the radial artery and adequate blood supply to the graft were preserved with a smooth plane of the sawdust provided. Avascular cortical-spongy allograft was cut out using the same guide (Fig. 2, d) corresponding to the marginal defect of the radius and the blood-supplied graft in length, thickness and shape and exceeding in width by 0.5 cm. Avascular allograft was placed in the defect of the radial bone and fixed with two wires and prophylactic plating of the radial bone performed (Fig. 2, e, f). The marginal avascular radial bone graft was congruent with the defect and adhered tightly to it. Vascularized radial bone graft together with a skin flap was transferred to the stump of the first metacarpal and the first finger reconstructed. The postoperative period was uneventful. The wounds healed by primary intention. The skin flap healed well indicating the preservation and functioning of the septal vessels. Evident signs of consolidation of the radial bone graft were identified at two months indicating the preservation of the periosteal vessels and the blood supply. No pathological fracture of the radius was detected at a long term with complete consolidation and reconstruction of the allograft achieved with complete elimination of the marginal defect (Fig. 2, f). The patient was examined at two years. The length of the reconstructed finger was 55 mm corresponding to the postoperative length of the intact first finger on the other side. The reconstructed finger had a functionally advantageous position. The bilateral grip of the hand was restored. The distance between the ends of the fifth finger and the reconstructed first finger is 19.5 cm with maximum abduction, as on a healthy hand. Pain and thermal sensitivity of the reconstructed finger were determined. The scar of the donor wound on the forearm was normotrophic and insignificant. The opposition function of the first finger was restored: the Kapangzhi test scored 9. Control radiographs of the left hand showed complete consolidation of the first metacarpal bone and the radial bone graft. The function of the first finger and hand grip were restored (Fig. 2, i, j). There were no signs of resorption of the reconstructed bone on the left side. Control radiographs of the forearm showed complete consolidation and replacement of the donor radial bone defect with an allograft at two years which was crucial for prevention of pathological fracture at the donor site.

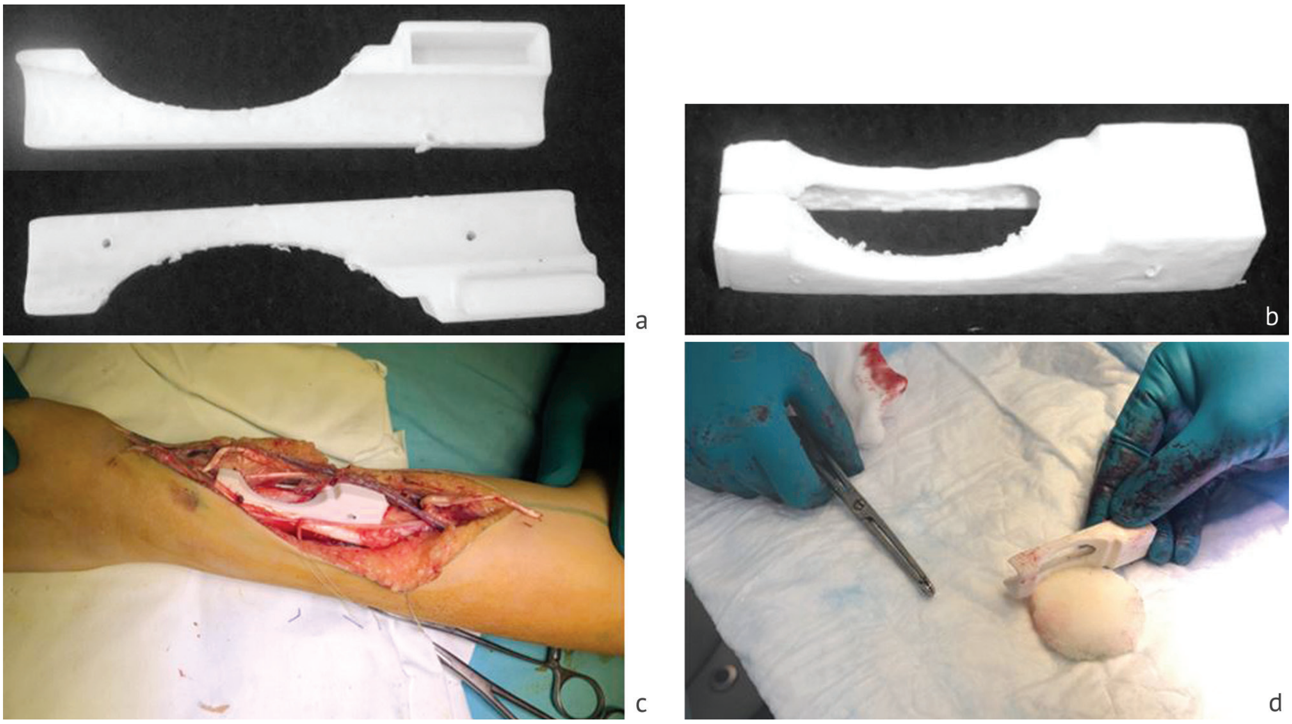
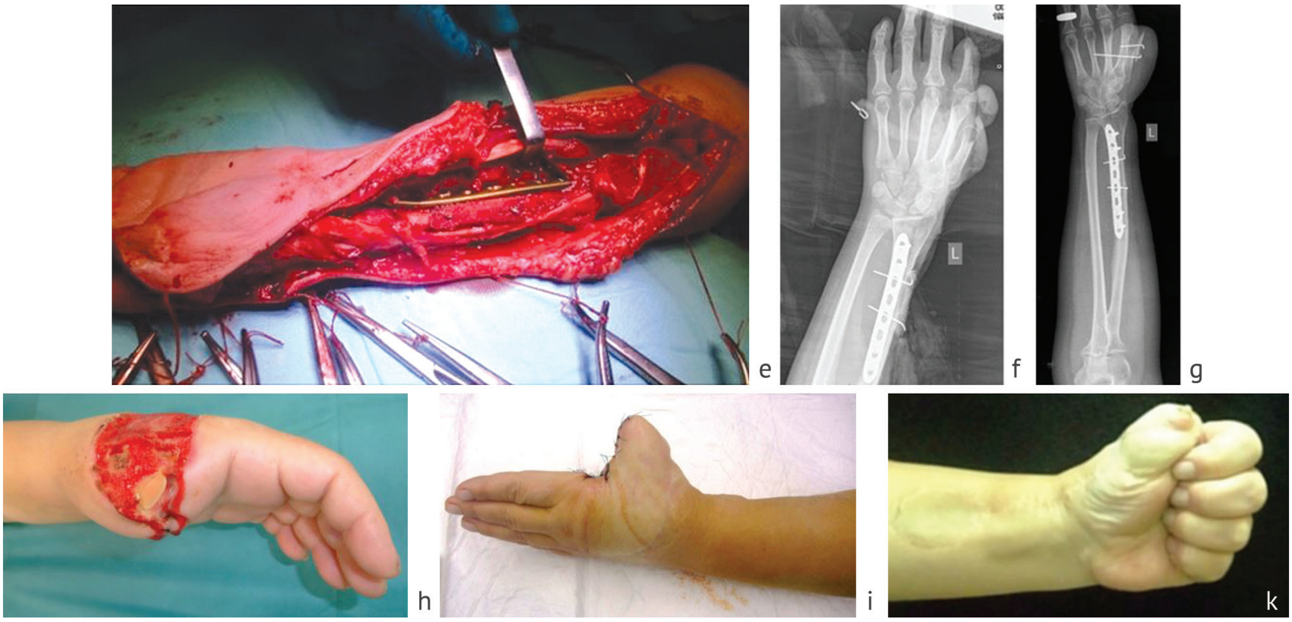


Fig. 2 A method for skin-bone reconstruction of the finger and a guide for its implementation: (*a*) components of the precision guide with the palmar and dorsal parts; (*b*) the guide assembled; (*c*) the guide used for vascularized grafting; (*d*) the guide used for corticocancellous allografting to replace the marginal defect of the radius



Continuation of the Fig. 2 A method for skin-bone reconstruction of the finger and a guide for its implementation: (*e*) alloplasty of the donor defect of the radius and plateing for prophylactic bone fixation; (*f*) postoperative radiograph of the hand and the forearm; (*g*) radiograph of the hand and forearm at one year; (*h*) preoperative appearance of the hand; (*i*) abduction of the first finger; (*j*) grip function of the hand

A 22-year-old patient A. was admitted to the PIMU hospital for the stumps of the 1st, 2nd, 3rd, and 4th fingers at the level of the proximal thirds of the main phalanges, the stump of the 5th finger at the level of the distal third of the main phalanx on the left side (Fig. 3, a). The patient was injured at work on 10/19/21 as a result of her hand getting caught in the rotating mechanism of the machine. Primary surgery was performed for the crushing injury of fingers I–V and the stumps of the fingers were formed. Necrosis of skin flaps at the ends of the finger stumps developed postoperatively. Soft tissue defects measured 2 cm by 6 cm ter debridement. Thin, ulcerating scars fused to the underlying bones were observed preoperatively at the ends of the stumps of the fingers with no grip of the hand (Fig. 3, a). Defects on the end surface of the stumps of fingers II–IV and finger I were previously replaced by plastic surgery with a Filatov stem to form a loop (06/04/22 and 17/05/22) (Fig. 3, b). The first stage of the stump lengthening of the first and second metacarpal bones was performed upon re-admission on September 14, 2022 to restore the function of bilateral hand grip using the technology developed (Fig. 3). The required cross-sectional dimensions of the first and second metacarpal bones were determined preoperatively at the mid level and at a distance of 0.5 cm from the middle. They turned to be equal to 10 mm. Hybrid parametric modeling and topology optimization were used to model a matrix and spacer of a hollow cylindrical shape such that its cross-section corresponded to the cross-section of the distracted metacarpal bone at a distance of 0.5 cm from the transverse osteotomy site. The length of the spacer was 1.5 cm, the thickness of the spacer wall was 1 mm. The spacer had a semi-open through longitudinal rectangular groove 2 mm wide and 1 cm long. A PLA matrix was made Using additive 3D printing technologies (Fig. 3, c). Transverse osteotomies of the first and second metacarpal bones were performed at the mid level. The matrix was filled with bone cement and a spacer formed as a hollow cylinder after hardening. The spacer was placed with a solid end on the proximal end of the distal fragment of the second metacarpal bone (Fig. 3, d). A Kirschner wire was placed intramedullary through the distal fragment of the metacarpal bone and the axial hole of the spacer. The proximal end of the wire was U-shaped with the short branch being inserted into the groove of the spacer until the bend area stopped at the end edge of the closed part of the groove and the proximal end of the distal fragment.

The distal end of the wire was pulled out. Another end of the wire was placed on the proximal fragment of the metacarpal bone. A similar distracting wire was placed on the first metacarpal bone without a spacer. The distal ends of the intramedullary wires were fixed to the screw rods of the Ilizarov reference ring. Gradual distraction of the metacarpal bones was performed postoperatively at a rate of 1 mm per day (Fig. 3, e). The bone fragments were separated by 35 mm. The second stage of distraction lengthening was performed on 15/11/22 with the external fixation device removed and an incision made along the postoperative scar. A well-defined hypervascular induced capsule developed in the distraction defect, extending 0.5 cm onto the ends of the bone fragments. The capsule had the same uniform wall thickness of 2 mm. The resulting capsule was dissected longitudinally along the distraction defect and the ends of the metacarpal bone fragments. The intramedullary wires and spacer were removed (Fig. 3, f). An endosteal bone regenerate 1.5 cm long developed at the proximal end of the distal fragment. Marginal lamellar bone regenerates 1 cm long and a mature regenerate shaped as a spur having a bone structure could be identified at the end of the proximal fragment. The distraction defect was repaired with a cortical-spongy allograft with the transverse dimensions not exceeding the outer diameter of the spacer (Fig. 3, g). The resulting distraction regenerates at the distal and proximal fragments were preserved. Osteosynthesis of bone fragments and grafts with wires was performed. The resulting osteogenic capsule was sutured with interrupted absorbable stitches over the graft and at the site of the contacts with metacarpal fragments (Fig. 3, h). The graft and the metacarpal contact site were completely covered with an osteogenic capsule. The subcutaneous tissue and skin over the osteogenic capsule were sutured in layers. The distraction regenerate was less pronounced in the first metacarpal bone. Plastic repair of the defect was performed using a cortical-spongy allograft fixed with wires (Fig. 3, i). The hand was immobilized with a plaster cast for five weeks. The wounds healed by primary intention. Primary healing of bone fragments and grafts being more pronounced on the second metacarpal bone was observed after removal of the cast. Two months later, the Filatov stem loop was divided with the distal portions of the first and second fingers formed. The patient was examined at six months postsurgery. The length of the first ray was 8 cm, the second ray was 9 cm. The distance between the ends of the stumps with the first ray abducted was 4 cm (Fig. 3, j). The treatment resulted in the function of bilateral hand grip restored (Fig. 3, k). The elongated stumps had adequate soft tissue coverage without signs of prolapse of the distal sections. Signs of consolidation and restructuring of allografts could be seen radiographically (Fig. 3, l).

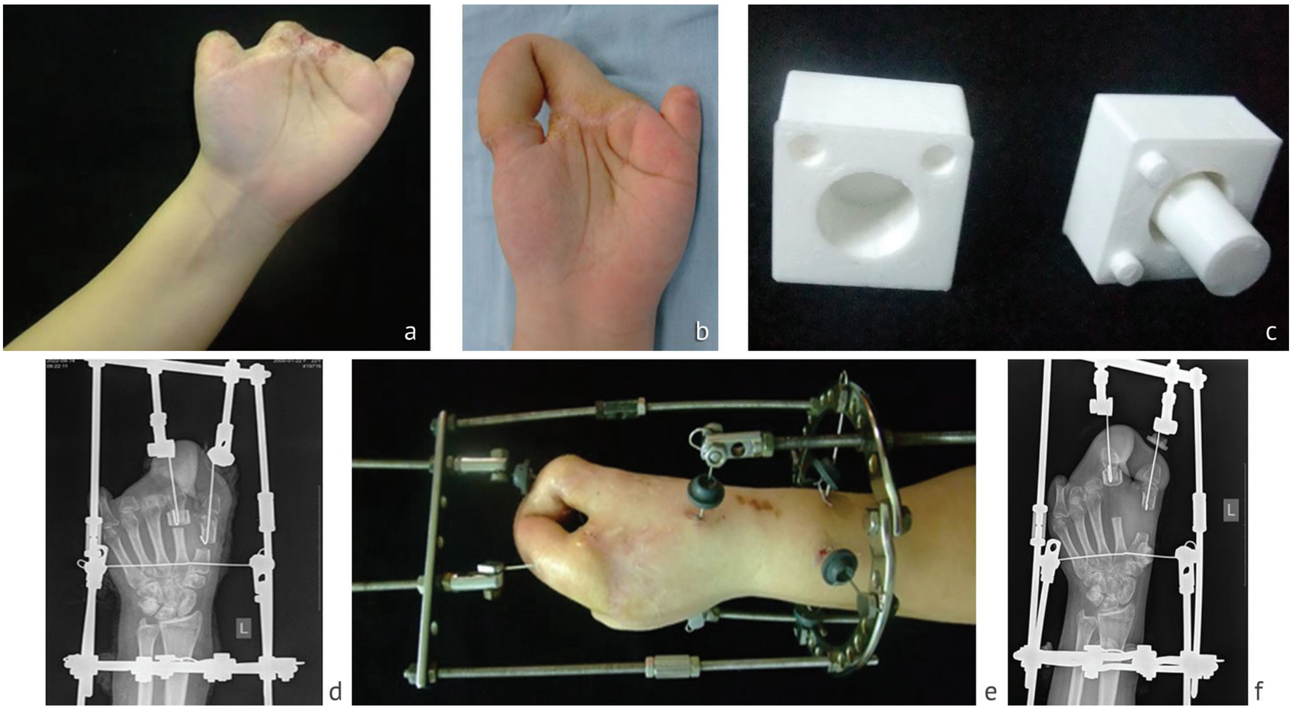
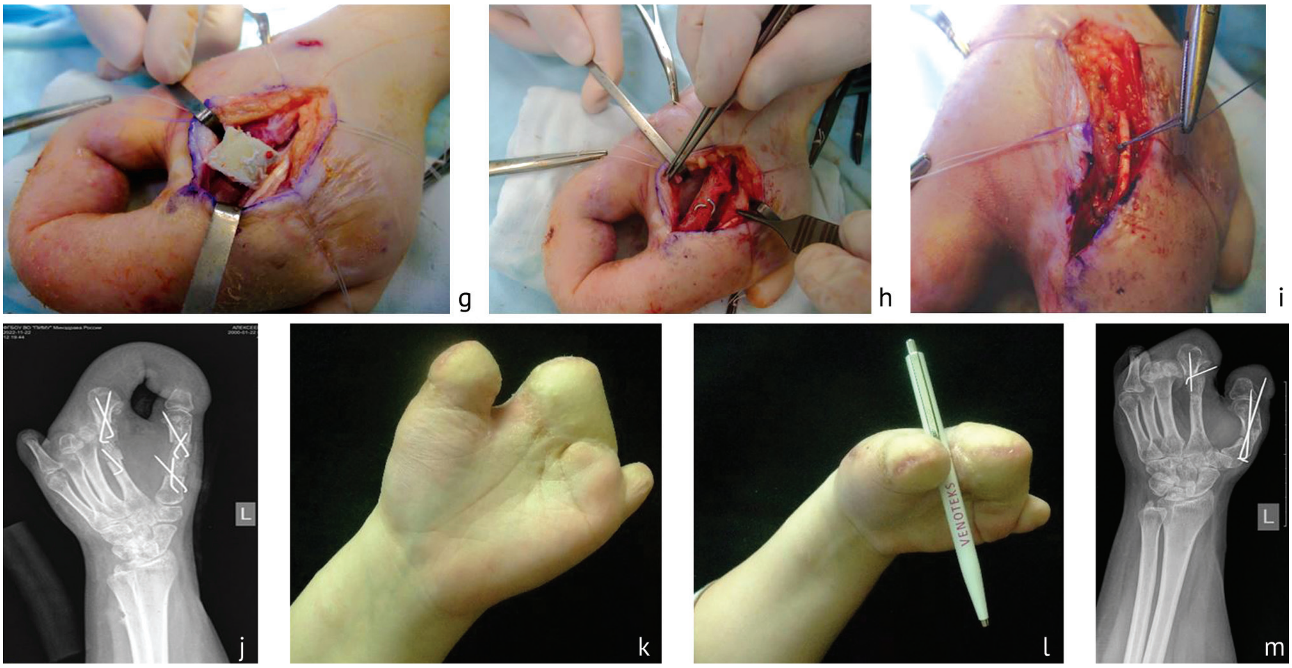


Fig. 3 Lengthening of the metacarpal stump: (*a*) preoperative appearance of the hand; (*b*) appearance of the hand after transplantation of the Filatov stem; (*c*) appearance of the matrix for intraoperative manufacturing of a hollow cylindrical spacer; (*d*) radiograph of the hand before the distraction of the stump of the second metacarpal bone together with a cylindrical spacer; (*e*) appearance of the hand after distraction with the Ilizarov frame; (*f*) radiograph of the hand after distraction of the stump of the second metacarpal bone together with a cylindrical spacer



Continuation of the Fig. 3 Lengthening of the metacarpal stump: (*g*) appearance of a cylindrical bone cement spacer after distraction; (*h*) the distraction defect of the second metacarpal bone replaced with a cortical-cancellous allograft; a well-defined induced membrane seen throughout the defect; (*i*) the inductive capsule sutured over the graft; (*j*) radiograph of the left hand after the second stage of reconstructive surgery; (*k*) abduction of the stump of the first ray; (*l*) hand grip; (*m*) radiograph of the hand at 6 months postsurgery

DISCUSSION

The effectiveness of reconstructive intervention is determined by its adequate planning. Preoperative 3D models for planning finger reconstruction are a rigid integral structure that does not allow changing the size and position of the components simulating phalanges of the finger in different planes. Well-known preoperative models are used in isolated absence of the first finger with no need for the functional position of the joints to be determined relative to the rest involved fingers [13, 14]. This makes the choice of the optimal position of the restored finger relative to the preserved segments of the hand difficult in case of a severe deformity. he known method of planning the length gain allows for the optimal length of the first finger to be identified for the distraction of the stump in each specific case, but it is not possible to determine the functionally advantageous position of the reconstructed finger relative to the rest of the fingers [20]. A tailored digital model with variable biomechanical parameters is created with the method offered, and the patient is involved in the preoperative planning. The model has adjustable biomechanical parameters including the length of the first finger, position of the phalanges in the joints and relative to the longitudinal axis. The device is an individual prefabricated construction with components being able of imitating the main and nail phalanges with the possibility of changing their position in the joints and rotational position, changing the length of the model of the main phalanx depending on the nature of the hand defect and the reconstruction method. The device helps to avoid corrective procedures for the reconstructed finger through changed position.

The problem of minimizing the donor defect during radial flap reconstruction is essential. Prevention of pathological fractures at the site of bone graft harvest is the most important thing in this case with the complications being a limiting factor in the use of the method. Reconstruction of the finger with a skin-bone radial flap suggests precise determination of the depth of the cut to prevent critical values and a fracture. Different approaches are used for this purpose to include rounded corners, locking holes, C-arm guided wires, use of a Mitchell trimmer, a screw depth gauge, a protective metal tape located in a longitudinal section, etc. which fail to provide sufficient precision marginal osteotomy of the radius [21, 22]. In addition to that, the osteotomy plane is not smooth enough with a scaphoid cutout, in particular, due to possible slipping of the saw blade off the rounded surface of the bone shaft. There is a risk of injury to the axial and septal vessels of the radial bone graft. Occasionally increased depth of the cut can significantly reduce bone strength. Some authors suggest intraoperative use of the marginal defect model created preoperatively as a template to follow during osteotomy [23]. This technique has similar disadvantages. For skin-bone reconstruction of a finger, we use 3D technologies for the basic stage of the operation harvesting a vascularized graft and preparing an allograft for plastic surgery of the marginal defect of the radius. A single-use instrument is created for a specific patient. A patient-specific 3D radius print allows for precise preoperative planning. No special tools could be found for such interventions in the available literature. We can create a tailored-made tool implementing our method for marginal osteotomy using 3D printing. The method helps to prevent undercutting (cutting) of the bone with smooth sawdust surface of the radial bone and the graft being formed to ensure the tight contact along the osteotomy plane. With the critical depth of the cut being exceeded, the device can optimize conditions for bone grafting by forming a graft that precisely matches the size, surface and shape of the marginal defect. The smooth surfaces of the osteotomy and allograft ensure the tight contact and optimal conditions for fusion and reconstruction during bone grafting to allow a qualitatively new result and restored structure of the donor bone. Depending on the clinical scenario, the guide can be created to form a scaphoid, rectangular, or any other graft shape.

In the last decade, the Masquelet method has become common in repair of bone defects of different etiology [24–28]. Some authors question the effectiveness of the technique [29]. There are reports about the advantages of combined distraction and the Masquelet technique to address bone defects. There is a known method of bone defect repair using a bone cement spacer to be placed in the tibial defect. The second stage of the procedure includes osteotomy and transport of the vascularized bone graft into the osteogenic capsule using the Ilizarov external fixation at the site of the osteoinductive membrane at 6–8 weeks [30]. However, the possibilities of this approach have not been explored in finger reconstruction. There is a risk of nonunion, fracture, prolapse and infection with use of interpositional graft with soft tissues scars, in particular [31, 32]. The need for soft tissue interventions in such unfavorable conditions with use of the Masquelet technology is emphasized by many authors [26]. The risk of the complications is minimized with the technique offered. Our method is based on the development and implantation of the original device consisting of a hollow cylindrical distractable spacer made of bone cement. The method ensures restoration of adequate soft tissue coverage of the stumps, formation of an osteogenic capsule, concurrent distraction of the stump, regeneration with the avascular bone interposition graft being surrounded by osteogenic membrane and vascularized tissues along the entire length and at the site of bone contact. Conditions for consolidation and graft reconstruction are improved in such cases preventing complications and reducing the treatment time.

CONCLUSION

The use of 3D printing technology in planning finger reconstruction using different methods, creation of tailored-made surgical instruments for plastic surgery using a skin-bone radial flap improved treatment results. The combined use of the distraction and the Masquelet method provided adequate functional results in finger reconstruction and prevention of complications in repair of an extensive soft tissue defect.

REFERENCES

1. Diment LE, Thompson MS, Bergmann JHM. Clinical efficacy and effectiveness of 3D printing: a systematic review. *BMJ Open*. 2017;7(12):e016891. doi: 10.1136/bmjopen-2017-016891
2. Matter-Parrat V, Liverneaux P. 3D printing in hand surgery. *Hand Surg Rehabil*. 2019;38(6):338-347. doi: 10.1016/j.hansur.2019.09.006
3. Wixted CM, Peterson JR, Kadakia RJ, Adams SB. Three-dimensional Printing in Orthopaedic Surgery: Current Applications and Future Developments. *J Am Acad Orthop Surg Glob Res Rev*. 2021;5(4):e20.00230-11. doi: 10.5435/JAAOSGlobal-D-20-00230
4. Mohammadi A, Lavranos J, Zhou H, et al. A practical 3D-printed soft robotic prosthetic hand with multi-articulating capabilities. *PLoS One*. 2020;15(5):e0232766. doi: 10.1371/journal.pone.0232766
5. Oud TAM, Lazzari E, Gijsbers HJH, et al. Effectiveness of 3D-printed orthoses for traumatic and chronic hand conditions: A scoping review. *PLoS One*. 2021;16(11):e0260271. doi: 10.1371/journal.pone.0260271

6. O'Brien L, Cho E, Khara A, et al. 3D-printed custom-designed prostheses for partial hand amputation: Mechanical challenges still exist. J Hand Ther. 2021;34(4):539-542. doi: 10.1016/j.jht.2020.04.005
7. Bauermeister AJ, Zuriarrain A, Newman MI. Three-Dimensional Printing in Plastic and Reconstructive Surgery: A Systematic Review. *Ann Plast Surg*. 2016;77(5):569-576. doi: 10.1097/SAP.0000000000000671
8. Mulford JS, Babazadeh S, Mackay N. Three-dimensional printing in orthopaedic surgery: review of current and future applications. *ANZ J Surg*. 2016;86(9):648-653. doi: 10.1111/ans.13533
9. Keller M, Guebeli A, Thieringer F, Honigmann P. Overview of In-Hospital 3D Printing and Practical Applications in Hand Surgery. *Biomed Res Int*. 2021;2021:4650245. doi: 10.1155/2021/4650245
10. Zhang D, Bauer AS, Blazar P, Earp BE. Three-Dimensional Printing in Hand Surgery. *J Hand Surg Am*. 2021;46(11):1016-1022. doi: 10.1016/j.jhsa.2021.05.028
11. Eltorai AE, Nguyen E, Daniels AH. Three-Dimensional Printing in Orthopedic Surgery. *Orthopedics*. 2015;38(11):684-687. doi: 10.3928/01477447-20151016-05
12. Tan H, Yang K, Wei P, et al. A Novel Preoperative Planning Technique Using a Combination of CT Angiography and Three-Dimensional Printing for Complex Toe-to-Hand Reconstruction. J *Reconstr Microsurg*. 2015;31(5):369-77. doi: 10.1055/s-0035-1546419
13. Zang CW, Zhang JL, Meng ZZ, et al. 3D Printing Technology in Planning Thumb Reconstructions with Second Toe Transplant. *Orthop Surg*. 2017;9(2):215-220. doi: 10.1111/os.12326
14. Xu L, Tan J, Wei P, et al. Clinical application of 3D printing technology for preoperative planning of thumb reconstruction. *Acta Ortop Bras*. 2021;29(4):211-218. doi: 10.1590/1413-785220212904235492
15. Lu H, Peng H, Peng Z, et al. The Application of Digital Design Combined with 3D Printing Technology in Skin Flap Transplantation for Fingertip Defects during the COVID-19 Epidemic. *Biomed Res Int*. 2021;2021:5554500. doi: 10.1155/2021/5554500
16. Gálvez JA, Gralewski K, McAndrew C, et al. Assessment and Planning for a Pediatric Bilateral Hand Transplant Using 3-Dimensional Modeling: Case Report. *J Hand Surg Am*. 2016;41(3):341-343. doi: 10.1016/j.jhsa.2015.12.010
17. Alexandrov NM, Veshaev ID. *Device for preoperative planning of reconstruction of the first finger of the hand*. Patent RF, no. 211603, 2022. Available at: https://new.fips.ru/registers-doc-view/fips_servlet?DB=RUPM&DocNumber=211603&TypeFile=html. Accessed Feb 13, 2024. (In Russ.)
18. Karyakin NN, Aleksandrov NM, Gorbatov RO, Veshaev ID. *A method for skin-osseous reconstruction of a finger and a guide for its implementation*. Patent RF, no. 2747694, 2021. Available at: https://www.fips.ru/registers-doc-view/fips_servlet?DB=RUPAT&DocNumber=2747694&TypeFile=html. Accessed Feb 13, 2024. (In Russ.)
19. Aleksandrov NM. *Method of distraction lengthening of the metacarpal stump*. Patent RF, no. 2796438, 2022. Available at: https://www.fips.ru/registers-doc-view/fips_servlet?DB=RUPAT&DocNumber=2796438&TypeFile=html. Accessed Feb 13, 2024. (In Russ.)
20. Koryukov A.A. *A device for determining the amount of elongation of the stump of the first finger*. Patent RF, no. 2796438, 2022. Available at: https://www1.fips.ru/Archive/PAT/2009FULL/2009.07.10/DOC/RUNWU1/000/000/000/084/215/DOCUMENT.PDF. Accessed Feb 13, 2024. (In Russ.)
21. Avery CM. Review of the radial free flap: still evolving or facing extinction? Part two: osteocutaneous radial free flap. *Br J Oral Maxillofac Surg*. 2010;48(4):253-260. doi: 10.1016/j.bjoms.2009.09.017
22. Shnayder Y, Tsue TT, Toby EB, et al. Safe osteocutaneous radial forearm flap harvest with prophylactic internal fixation. *Craniomaxillofac Trauma Reconstr*. 2011;4(3):129-136. doi: 10.1055/s-0031-1279675
23. Capito AE, Hansen BK, Schmitt MW, et al. Osteocutaneous Radial Forearm Flap: Harvest Technique and Prophylactic Volar Locked Plating. *Plast Reconstr Surg Glob Open*. 2023;11(11):e5449. doi: 10.1097/GOX.0000000000005449
24. Masquelet AC, Begue T. The concept of induced membrane for reconstruction of long bone defects. *Orthop Clin North Am*. 2010;41(1):27-37. doi: 10.1016/j.ocl.2009.07.011
25. Lasanianos N Kanakaris N, Giannoudis P. Current management of long bone large segmental defects. *Orthopedics and Trauma*. 2010;24(2):149-163. doi: 10.1016/j.mporth.2009.10.003
26. Gupta G, Ahmad S, Mohd Zahid, et al. Management of traumatic tibial diaphyseal bone defect by "induced-membrane technique". *Indian J Orthop*. 2016;50(3):290-296. doi: 10.4103/0019-5413.181780
27. Ayouba G, Lemonne F, Kombate NK, et al. Interest of nailing associated with the Masquelet technique in reconstruction of bone defect. *J Orthop*. 2019;20:228-231. doi: 10.1016/j.jor.2019.12.014
28. Mi M, Papakostidis C, Wu X, Giannoudis PV. Mixed results with the Masquelet technique: A fact or a myth? *Injury*. 2020;51(2):132-135. doi: 10.1016/j.injury.2019.12.032
29. Morris R, Hossain M, Evans A, Pallister I. Induced membrane technique for treating tibial defects gives mixed results. *Bone Joint J*. 2017;99-B(5):680-685. doi: 10.1302/0301-620X.99B5.BJJ-2016-0694.R2
30. Borzunov DYu, Mokhovikov DS, Kolchin SN, Gorbach EN. Combined use of the Ilizarov non-free bone plasty and Masquelet technique in patients with acquired bone defects and pseudarthrosis . *Genij Ortopedii*. 2020;26(4):532-538. doi:10.18019/1028-4427-2020-26-4-532-538
31. Heo CY, Kwon S, Back GH, Chung MS. Complications of distraction lengthening in the hand. *J Hand Surg Eur Vol*. 2008;33(5):609-615. doi: 10.1177/1753193408090767
32. Erdem M, Sen C, Eralp L, et al. Lengthening of short bones by distraction osteogenesis--results and complications. *Int Orthop*. 2009;33(3):807-813. doi: 10.1007/s00264-007-0491-x

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