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Surgical Technique

Targeted Muscle Reinnervation and the Volar Forearm Filet Flap for Forequarter Amputation: Description of Operative Technique

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Targeted muscle reinnervation after upper-extremity amputation has demonstrated improved outcomes with myoelectric prosthesis function and postoperative neuropathic pain. This technique has been established in the setting of shoulder disarticulation as well as transhumeral and transradial amputations, but a detailed technique of targeted muscle reinnervation with free tissue transfer from the volar forearm after forequarter amputation has not yet been described. Here, we describe a technique using a volar forearm filet flap to achieve simultaneously satisfactory soft tissue coverage after resection of a tumor from the chest wall and targeted muscle reinnervation of the brachial plexus.

Forequarter amputation was initially described in the setting of severe upper-extremity trauma and now more commonly has a role in tumor surgery when limb salvage techniques are not an option. Unfortunately, prosthetic use after forequarter amputation requires great expenditure of energy and can be cumbersome. Phantom pain can be present in 85% of patients with forequarter amputations or shoulder disarticulations; residual stump pain may contribute to only 40% use of prosthetics in this group.[1]

Targeted muscle reinnervation (TMR) after upper-extremity amputation has gained popularity over the past decade to enhance myoelectric prosthesis function and decrease both neuroma pain and phantom pain.[2–5] A recent randomized controlled trial[4] also demonstrated a trend toward improved postoperative neuroma and phantom limb pain in amputees with chronic pain who underwent TMR compared with traditional neurectomy.

Targeted muscle reinnervation technique employs the transfer of amputated nerves into motor branches of residual target muscles, which then serve to amplify EMG signals that can be detected by surface electrodes connected to the prosthesis.[6] Targeted muscle reinnervation allows for improved myoelectric prosthesis use and cortical control of the prosthesis to restore not only primary extremity functions of elbow flexion-extension and hand opening and closing but also coordinated motions such as elbow flexion combined with handgrip. Myoelectric testing and prosthesis fitting usually occur after 6 months.[7]

These transfers have been described in the setting of shoulder disarticulation as well as transhumeral and transradial amputations.[7–10] Targeted muscle reinnervation has also been used in conjunction with spare-parts surgery to restore function after mangling limb injuries.[11] As in other upper-extremity amputations, TMR through free flap transfer after forequarter amputation and chest wall reconstruction offers a similar opportunity to reduce postamputation neuroma and phantom limb pain.[2,3,5]

This article describes the technique for free tissue transfer incorporating TMR using a musculocutaneous, spare-parts filet flap of the volar forearm after forequarter amputation and chest wall reconstruction for recurrent sarcoma involving the shoulder girdle. In this technique, the muscles within the volar forearm filet flap serve as end targets for nerve transfers from the trunks of the brachial plexus. Although free volar forearm filet flap has been described for soft tissue coverage after forequarter amputation in a small series,[12] to the authors' knowledge, the technique for TMR in this setting has not yet been detailed in the literature.

Declaration of interests: No benefits in any form have been received or will be received by the authors related directly or indirectly to the subject of this article.

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Figure 1. The patient is positioned in the lateral decubitus position with the operative arm prepared for surgery into the sterile field for manipulation during forequarter amputation. A large skin flap is preserved over the lateral deltoid to facilitate soft tissue coverage. This patient had a prior rotational pectoralis major flap and skin grafting from an oncologic resection, which was complicated by tumor recurrence.

Indications and Contraindications

To perform TMR with free tissue transfer after forequarter amputation, muscle and neurovascular structures must be viable distal to the resection. Patients undergoing oncologic resection must have disease-free tissue distally, and trauma patients must have tissue that is not overly traumatized distally but that is unable to undergo limb salvage.

Patients are not candidates if they have associated brachial plexus or spinal cord injuries, because available donor nerves for muscle reinnervation are compromised. Patients must also be aware of the considerable postoperative rehabilitation required after TMR and be able and willing to comply. Because the technique discussed involves free tissue transfer, comorbidities that would compromise flap viability may preclude patients from free tissue transfer for TMR. These include peripheral vascular disease, irradiated or damaged transfer tissue, an inability to tolerate prolonged anesthesia, ongoing infection, and other notable medical comorbidities that increase the risk for vascular embarrassment. There is no definitive age restriction for performing TMR in this setting, but nerve transfers demonstrate improved outcomes in younger patients.[13]

Surgical Anatomy

Traditional muscle targets used for TMR in proximal upper-extremity amputations include the pectoralis major, serratus anterior, and latissimus dorsi.[7,14,15] However, after forequarter amputation, these muscles may not be available depending on prior surgery or the extent of resection in the setting of oncologic surgery or trauma. Free tissue transfer from the volar forearm can bypass this issue by providing different muscle targets for reinnervation. In this case, nerve transfer to the median nerve within the flap provides reinnervation of the pronator teres, flexor digitorum superficialis, flexor digitorum profundus to the index and middle fingers, flexor carpi radialis, flexor pollicis longus, and palmaris longus. Nerve transfer to the ulnar nerve provides reinnervation of the flexor carpi ulnaris (FCU) and flexor digitorum profundus to the ring and little fingers. Finally, nerve transfer to the radial nerve provides reinnervation to the brachioradialis within the flap.

The anatomy of the brachial plexus is an important consideration in this technique. After forequarter amputation, the resection typically extends through the clavicle, and the brachial plexus is truncated at the level of the trunks or divisions, which then serve as the donor nerves for reinnervation into the more peripheral radial, ulnar, and median nerves of the free flap. A size mismatch is expected, but the large brachial plexus trunks provide hyperinnervation, which promotes target muscle reinnervation.[16]

Surgical Technique

The patient is placed in the lateral decubitus position with the arm prepared for surgery and free to allow for manipulation during the forequarter amputation. The incision for the forequarter amputation is marked out, preserving as much of a skin flap over the lateral deltoid as permissible based on the oncologic resection to facilitate soft tissue coverage (Fig. 1). After the clavicle is cut, the subclavian vessels are identified, tied off, and transected to facilitate amputation and subsequently prepared for the flap pedicle anastomosis. The anterior and posterior divisions of the upper, middle, and lower trunks of the brachial plexus are then dissected. These serve as the nerve donors for TMR after revascularization of the free tissue transfer.

The remainder of the forequarter amputation is carried out based on oncologic principles, with the appropriate margin dictated by the specific tumor subtype. After the amputation is completed, the extremity is taken to the sterile back table to perform harvest of the volar forearm filet flap. A second, clean instrument setup is used going forward, again in accordance with oncologic principles. A longitudinal incision is made over the dorsal forearm, in line with the lateral epicondyle and the third metacarpal (Fig. 2). Sharp dissection is carried down through skin. Full-thickness flaps are elevated and subfascial dissection is continued radially and ulnarly, leaving the extensor tendons and extensor retinaculum adherent to the dorsal aspect of the radius and ulna. The dorsal edge of the brachioradialis forms the radial margin of the superficial dissection. Once this is found, the volar dissection proceeds deep to the muscles of the volar forearm. The radial artery and superficial branch of the radial nerve (SBRN) are identified distally. The artery is ligated at the distal edge of the flap and divided, and the SBRN is cut under tension and cauterized for later burying within the flap. The contents of the volar forearm compartment are then elevated off the interosseous membrane, including pronator quadratus with the flap, using a combination of sharp and blunt dissection or electrocautery. All volar vessels should be protected during this process. Care should be taken to protect the radial artery as it dives deep to the brachioradialis in the middle third of the forearm.

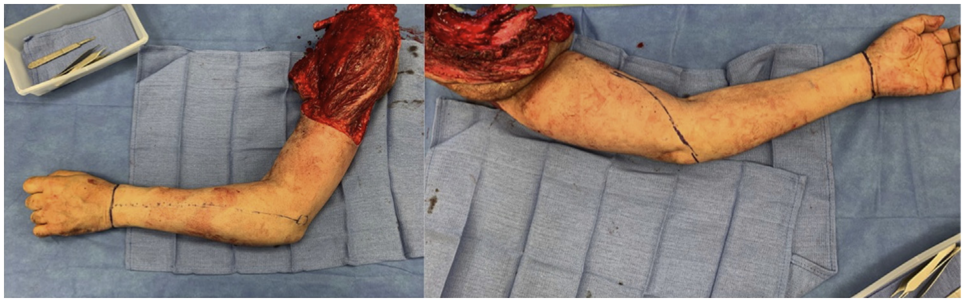

Figure 2. The incisions for the volar myocutaneous flap are marked. A longitudinal incision is drawn on the dorsum of the forearm from the lateral epicondyle to the third metacarpal.

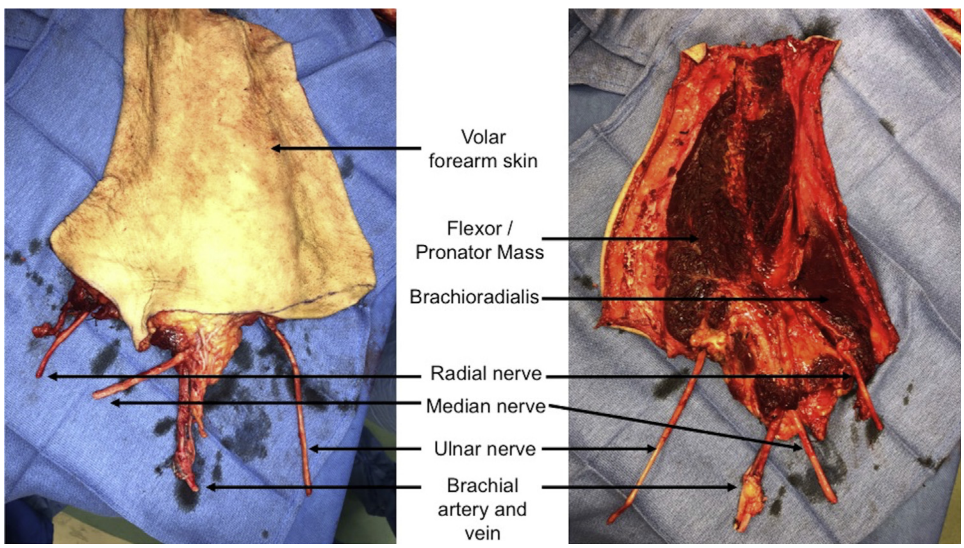

Figure 3. The radial, median, and ulnar nerves as well as the brachial artery and vein are identified and dissected free in the in the proximal brachium.

On the ulnar side of the wrist, periosteal dissection is carried out between the extensor carpi ulnaris and FCU. The FCU muscle and tendon are lifted with the volar flap, while the extensor carpi ulnaris remains with the amputated limb. Dissection of the volar flap is performed on both sides, working from radial to ulnar and ulnar to radial. The ulnar artery is also identified and ligated at the distal edge of the flap; care is taken to minimize any proximal dissection around the artery to preserve surrounding volar and dorsal skin perforators. The median and ulnar nerves are also identified distally and transected with the distal ends marked to facilitate coaptation to each other after flap revascularization. Elevation of the flap then proceeds along the forearm in a distal to proximal manner.

At the proximal aspect of the flap, the median, ulnar, and radial nerves, as well as the brachial artery, are identified at the level of the elbow and dissected free to the level of the mid-brachium. Veins for anastomosis to the recipient site are also identified and ligated. The flap is then fully separated from the forearm with the median, radial, and ulnar nerves, brachial artery, and associated veins (Fig. 3).

The flap is transferred onto the chest wall and provisionally inset with skin staples. The subclavian artery is identified, and a vascular clamp is placed proximally. The ligature is cut, and after flashing the artery to confirm flow, anastomosis is performed to the brachial artery in the flap with 7-0 polypropylene suture. Given the caliber of the vessels, this anastomosis can be done under loupe magnification (Fig. 4). Similarly, a clamp is placed on the subclavian vein, the ligature is removed and a fresh cut is made in the vein. Anastomosis is then performed between the largest vein of the flap with the subclavian vein. The size mismatch between the subclavian vein and the flap vein is reduced by sharply beveling the flap vein in an oblique fashion. Both clamps are removed and flow into the flap is confirmed. Then, 5,000 units of intravenous heparin are given by the anesthesia team, according to our standard protocol with free tissue transfer. Careful hemostasis should be obtained with a combination of electrocautery and ligature clips.

The nerve transfers are performed after vascular anastomoses are complete. The anterior and posterior divisions of the upper trunk of the brachial plexus are coapted to the radial nerve using interrupted 7-0 polypropylene or 8-0 nylon suture, depending on

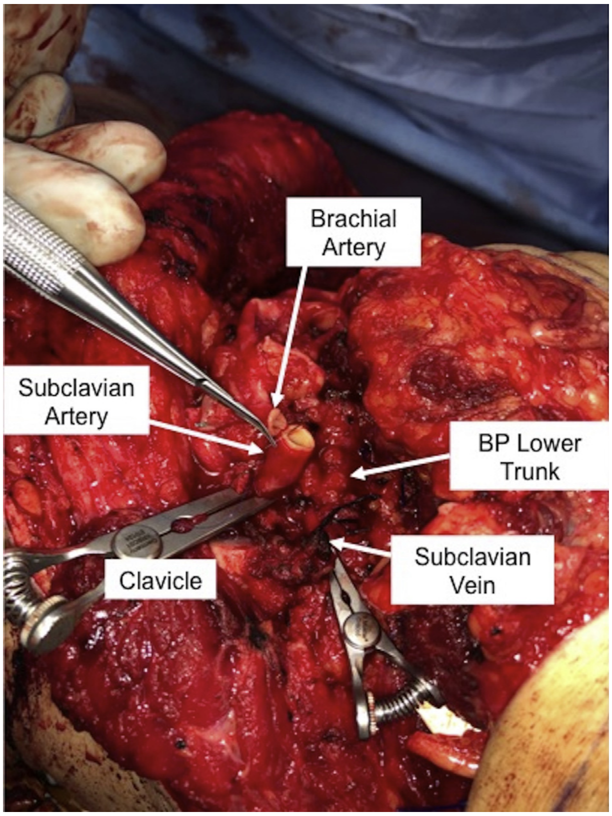

Figure 4. After completion of the forequarter amputation, the trunks of the brachial plexus (BP) are dissected and prepared for eventual anastomosis to the distal peripheral nerve branches within the free flap. Vascular clamps have been placed on the subclavian artery and vein. The brachial artery has been sharply beveled in preparation for anastomosis to the subclavian artery to accommodate the size mismatch.

the surgeon's preference. The SBRN on the undersurface of the flap is buried into the brachioradialis muscle belly using interrupted 7-0 polypropylene sutures to prevent terminal neuroma formation after regeneration of the upper trunk. In some cases, the SBRN can be coapted to a proximal sensory nerve such as the supraclavicular sensory nerve. The ulnar nerve is coapted to the anterior and posterior divisions of the lower trunk in a similar fashion, and the median nerve is coapted to the anterior and posterior divisions of the middle trunk (Fig. 5).

The ends of the median and ulnar nerves at the distal edge of the flap are also identified and coapted in an end-to-end manner to perform a centrocentral coaptation and prevent distal neuroma pain, given the size of these nerves. This technique has been used to prevent and manage painful neuroma formation in the lower extremity and hand.[17–20] However, in the setting of a more proximal TMR, it remains experimental. We thought that a centrocentral anastomosis provided a good option to address the possibility of a painful stump neuroma proactively after median and ulnar nerve reinnervation. This can also be performed with 7-0 polypropylene or 8-0 nylon suture. Fibrin glue can be used to augment the coaptation sutures.

The remaining skin flap that was elevated from over the lateral deltoid is then employed with the free flap to cover the chest wall defect (Fig. 6). A pain catheter can be placed at this point around the brachial plexus for postoperative pain control. Surgical drains are placed beneath the flaps and sutured in place, and remain until there is minimal output after surgery (<30 mL over 24 hours). The incisions are closed carefully, and Doppler signals are confirmed over the flap before applying the surgical dressing. Doppler signals are marked with a 2-0 polydioxanone suture to facilitate postoperative monitoring. A window is left within the bulky soft dressing to allow assessment of flap color and Doppler evaluation.

Postoperative Management

If a chest wall resection is performed, the patient is initially admitted to a surgical intensive care unit for pulmonary monitoring. The flap is checked hourly with a Doppler and visual assessment by nursing staff for the first 24 hours while the patient is allowed to take nothing by mouth. Antibiotics are continued per standard routine. We prefer to use 325 mg aspirin daily and dipyridamole 25 mg 3 times a day to prevent thromboembolism. If the flap appears viable at 24 hours after surgery, the patient is allowed a standard diet, but caffeine and tobacco are prohibited. The patient is monitored in a step-down unit for the next 3 days and then transitioned to the floor. Sutures and drains are removed at 2 weeks.

Pearls and Pitfalls

- Because this technique is typically employed in the setting of a shared case with an orthopedic oncologist and/or cardiothoracic surgeon, the hand surgeon should be present during incision planning to preserve as much of the native deltoid skin as safely possible to aid in soft tissue coverage.
- During dissection of the free flap, the surgeon should avoid dissecting circumferentially around the radial and ulnar arteries, which risks disrupting volar and dorsal skin perforators.
- During flap harvest, dissection of the radial, ulnar, and median nerves into the proximal brachium ensures enough length for TMR without undue tension.
- During flap anastomosis, sharply beveling the smaller caliber brachial artery and vein can reduce the size mismatch with the subclavian vessels.

Case Illustration

A 60-year-old, right-handed man had a recurrent left axillary sarcoma. Two years earlier, he had undergone tumor resection, scapula resection, and rotational pectoralis major flap for soft tissue coverage. He had also had 2 previous tumor resection attempts at a different hospital that unfortunately were complicated by recurrence. Given the aggressive nature of the malignancy and involvement of the chest well with the most recent recurrence, he underwent left forequarter amputation with chest wall resection and reconstruction with Gore-Tex graft (GORE-TEX Soft Tissue Patch, W.L. Gore & Associates, Newark, DE). We then performed a left volar forearm musculocutaneous filet flap with TMR of the anterior and posterior divisions of the upper trunk to the radial nerve, middle trunk to the median nerve, and lower trunk to the ulnar nerve. The patient had complete healing of the volar forearm flap, and sutures were removed at 2 weeks. However, by 4 weeks after surgery, he was found to have a draining sinus communicating with the anterior native skin, owing to a deep infection beneath the Gore-Tex graft (Fig. 7). The flap was elevated without difficulty to allow removal of the Gore-Tex graft by the cardiothoracic surgeons, and the

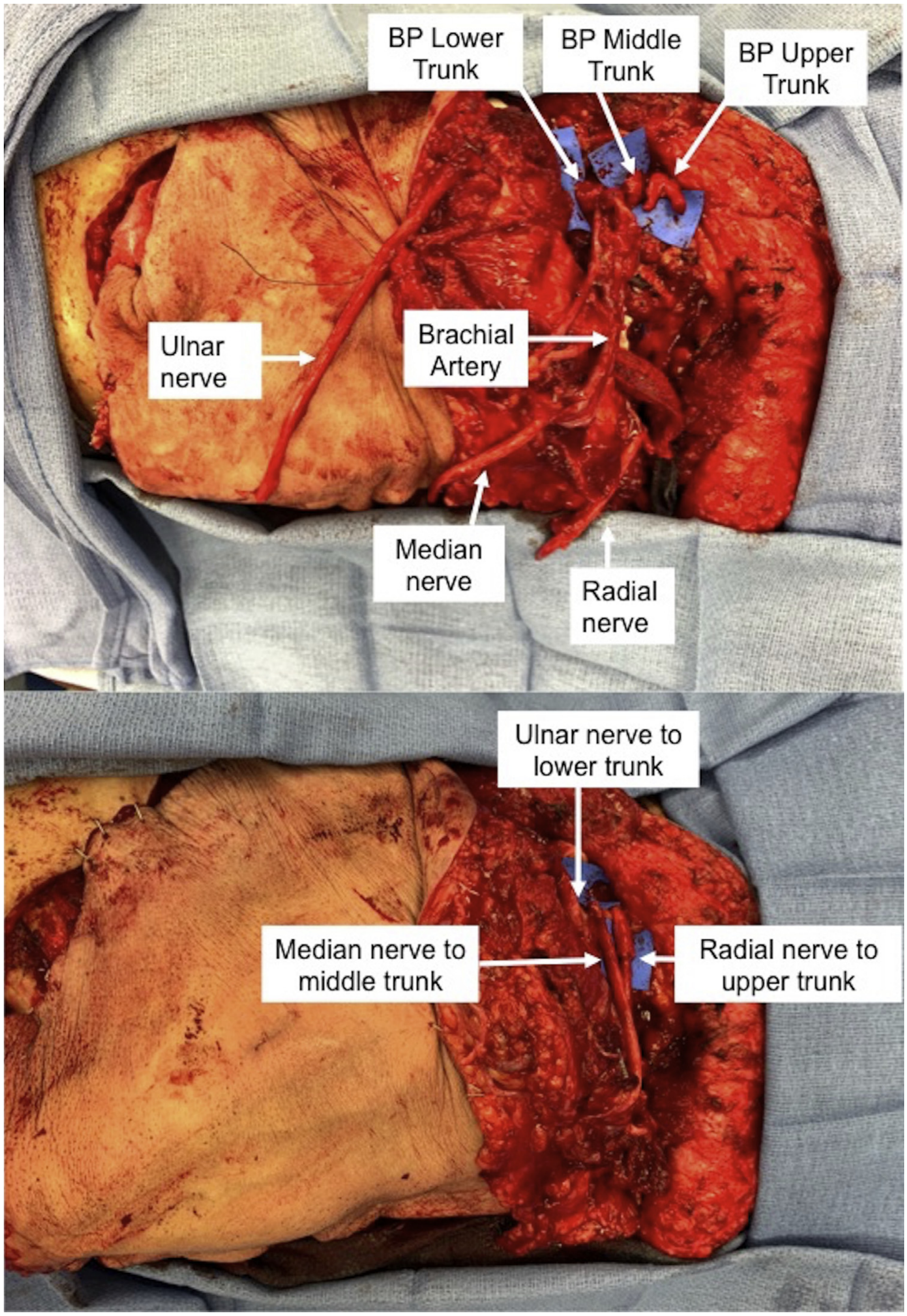

Figure 5. The trunks of the brachial plexus (BP) are isolated for coaptation to the peripheral nerves within the free flap.

patient was then given intravenous antibiotics. Pain was managed initially with oxycodone and subsequently with tramadol.

Complications

Complications of free flap transfer for TMR include infection, flap failure, failure of reinnervation of the target muscles within the flap, and persistent phantom limb pain. The risk for flap failure itself is decreased by using large-caliber vessels such as the subclavian vessels in the recipient site and the brachial artery in a volar forearm filet flap. In the case illustration, the flap survived without complication, but deep infection related to the chest wall reconstruction required a secondary surgery. The advantage of the well-vascularized musculocutaneous flap is that it permitted incision and primary closure of the wound without difficulty.

Ultimately, free flap transfer for TMR serves as a way to enhance prosthetic function after a proximal amputation (such as a forequarter amputation) by providing muscle targets for reinnervation that would otherwise no longer be available. It also provides a supple soft tissue envelope that can be valuable in covering these complex wounds. Similar to TMR after shoulder disarticulation and

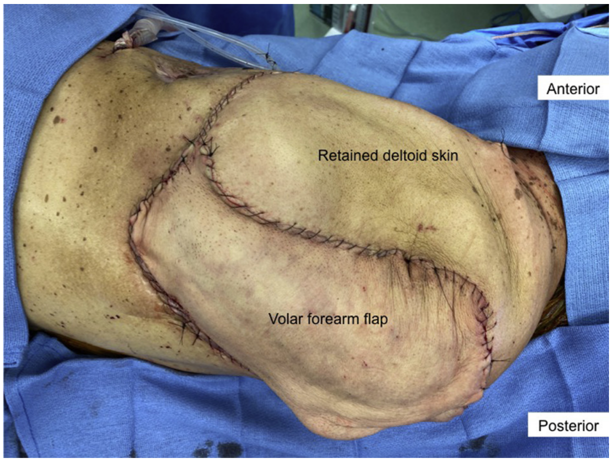

Figure 6. The retained deltoid skin flap and free flap have been arranged to cover the surgical bed. A chest tube is seen and was placed during the chest wall reconstruction before the free flap was set in.

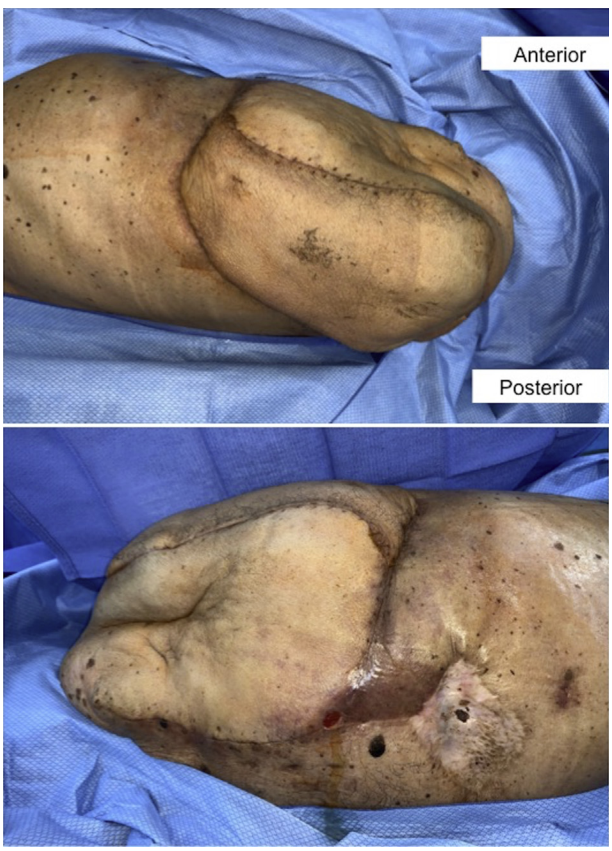

Figure 7. Four weeks after surgery, the flap is healed but noted to have a draining sinus anteriorly beneath the native deltoid skin from a surgical site infection deep to the Gore-Tex graft.

transhumeral and transradial amputation, free flap transfer for TMR can serve as a means to decrease postamputation nerve pain.

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