Computed Tomographic Angiography Perforator Localization for Virtual Surgical Planning of Osteocutaneous Fibular Free Flaps in Head and Neck Reconstruction

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Virtual surgical planning (VSP), computer-aided design and computer-aided modeling, and 3-dimensional printing are 3 distinct technologies that have become increasingly employed in head and neck oncology and microvascular reconstruction. Although each of these technologies have long been utilized for treatment planning in other surgical disciplines such as craniofacial surgery, trauma surgery, temporomandibular joint surgery, and orthognathic surgery, its widespread use in head and neck reconstructive surgery remains a much more recent advent. In response to the growing trend of VSP being used for the planning of fibular free flaps in head and neck reconstruction, some surgeons have questioned the technology's implementation based upon its perceived inadequacy in addressing other reconstructive considerations beyond hard tissue anatomy. Detractors of VSP for head and neck reconstruction highlight its lack of capability in accounting for multiple reconstructive factors, such as recipient vessel selection, vascular pedicle reach, need for dead space obliteration, and skin paddle perforator location. It is with this premise in mind that we report a simple technique for anatomically localizing peroneal artery perforators during VSP for osteocutaneous fibular free flaps in which both bone and a soft tissue skin paddle are required for ablative reconstruction. The technique allows for anatomic perforator localization during the VSP session based solely upon data existent within the preoperative computed tomographic angiography (CTA) and it does not require any modifications to preoperative clinical workflows. It is the authors' presumption that many surgeons in the field are unaware of this planning capability within the context of modern VSP for head and neck reconstruction. The primary purpose of this manuscript is to introduce and further familiarize surgeons with the technique of CTA perforator localization as a method of improving intraoperative fidelity for VSP of osteocutaneous fibular free flaps.

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Virtual surgical planning (VSP), computer-aided design (CAD) and computer-aided modeling, and 3-dimensional (3D) printing are 3 distinct technologies that have become increasingly employed within head and neck oncology and microvascular reconstruction. Although each of these technologies have long been utilized for treatment planning of craniofacial surgery,[1,2] trauma surgery,[3-5] temporomandibular joint surgery,[6,7] and orthognathic surgery,[8,9] its widespread implementation in head and neck surgery, and specifically composite microvascular free tissue transfer, is a much more recent advent. Although some have been quick to adopt the technology as a method of decreasing the time and difficulty of executing complex maxillofacial reconstructions, others have highlighted the current technological shortcomings of these adjunctive techniques.[10] Proponents of VSP for head and neck reconstruction have cited improved intraoperative efficiency, increased accuracy of reconstruction, decreased intraoperative ischemia time, increased predictability of surgical outcomes, improved patient satisfaction, and decreased complication rates.[11-24] However, there remains a subset of reconstructive surgeons who contend that VSP ignores many other important aspects of composite maxillofacial reconstruction—particularly those pertaining to soft tissue considerations, such as recipient vessel selection, pedicle reach, soft tissue requirements, need for dead space obliteration, and skin paddle perforator localization.[10] These contentions remain a viable concern for reconstructive surgeons, because VSP in its current form does not possess the capability of comprehensively addressing all these important reconstructive soft tissue considerations. At our own institution, the reconstructive surgeons initially resistant to the use of VSP for fibular free flap reconstructions often highlighted the technique's deficiency in planning for composite defects in which both bone and a soft tissue skin paddle were required for the ablative defect. The strongly held contention was that the preoperatively unknown location of the skin paddle perforator would potentially preclude the accurate application of the patient-specific cutting guide in the circumstance that the location of the perforator did not coincide favorably with the preplanned osteotomy segments. Thus, the accuracy and fidelity of the preoperative virtual surgical plan would be obviated by the need to intraoperatively modify the plan by translocating the cutting guide along the fibula to "capture" a more favorable relation between the bone and skin paddle perforator or perhaps even abandoning the entire virtual surgical plan in favor of the traditional "freehand" technique. Although the latter scenario remains quite uncommon in the execution of a well-devised virtual surgical plan, the former scenario does introduce the potential for small degrees of surgical inaccuracy that, if compounded over the course of a complicated procedure, will invariably lead to intraoperative discrepancies that will need to be manually remedied by the surgeon in order to obtain a satisfactory outcome. Those well versed in the nuances of VSP understand that the true realized benefit of the technology is only evident when the surgeon can reproduce the virtual surgical plan with a high level of intraoperative fidelity. Poorly devised or unrealistic virtual surgical plans taken to the operating room without a combined understanding of hard and soft tissue constraints can be fraught with intraoperative complications and can lead to devastating consequences for the patient and acceptance of potentially avoidable suboptimal outcomes. In this regard, the greater anatomic information available to the surgeon at the outset of the VSP session enables a higher degree of foresight being employed during the planning session and subsequently allows for a higher level of precision in executing that plan intraoperatively. It is with this premise in mind that that we report a straightforward technique for anatomically localizing peroneal artery perforators during VSP for osteocutaneous fibular free flaps in which bone and a soft tissue skin paddle are required for ablative reconstruction. The technique is unique in that it allows for anatomic perforator localization during the VSP session based solely on the data existent within the preoperative computed tomographic angiography (CTA) and does not require any pre-VSP clinical Doppler mapping of perforator locations.

Technique

At the authors' institution, the preoperative vascular study of choice to verify patent 3-vessel runoff from the popliteal artery before harvest of a fibular free flap is the CTA. The lower-extremity CTA images obtained at our institution are procured on dual-source 128-slice multidetector CT scanners (Somatom Definition Flash, Siemens, Erlangen, Germany) using arterial phase imaging with intravenous nonionic iodinated contrast media and a bolus tracking technique for timing of imaging acquisition. Exported CTA images available for clinician review include high-resolution axial cuts with 2-mm slice thickness along with both coronal and sagittal reformats with equivalent slice thickness.

The first step in localizing perforators using this technique is for the surgeon to carefully scrutinize the high-resolution CTA images in the axial plane to identify the takeoff of a suitably positioned cutaneous perforator from the peroneal artery (Fig 1). This can be performed before the VSP session so that the surgeon pre-emptively knows where the osteotomies should

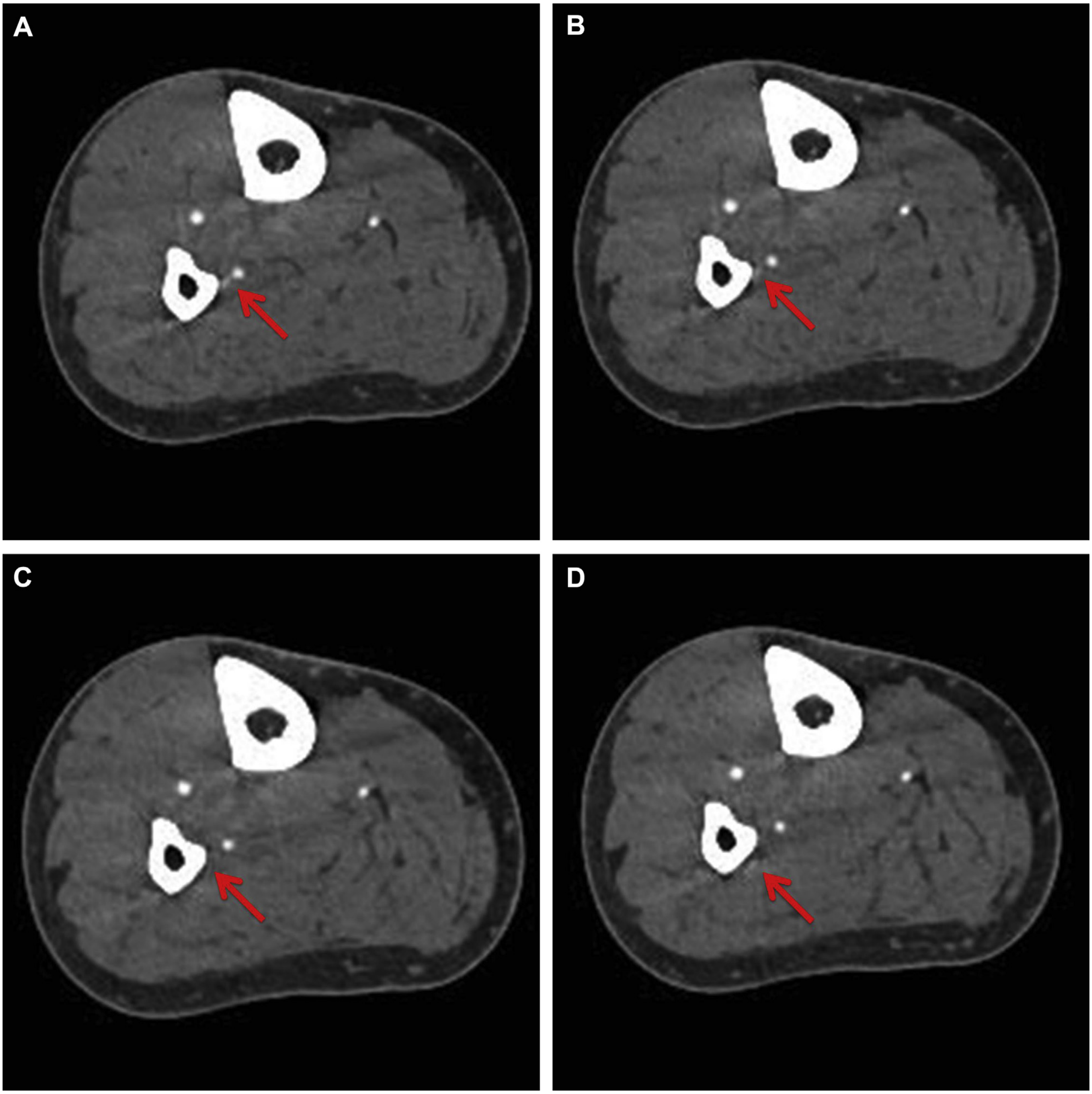

FIGURE 1. Axial slices from computed tomographic angiography data of the right lower extremity depicting a cutaneous perforator takeoff from the peroneal artery. *A-H*, Proceeding from proximal to distal, the *red arrow* delineates the course of the septocutaneous perforator from its takeoff from the peroneal artery to its termination in the skin of the lateral leg.

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be planned or it can be completed during the planning session with the biomedical engineer present. Before the VSP session, the biomedical engineer will import the CTA Digital Imaging and Communications in Medicine (DICOM) data into Mimics Medical 19.0 (Materialise, Leuven, Belgium) to convert the anatomy into 3D objects. Once the perforator is identified, the biomedical engineer or the surgeon can place markers along the course of the perforator with the "spline" feature of the Mimics Medical software's Analyze module. A secondary ancillary benefit of localizing the perforator in this fashion is that the tracing will also inherently provide the surgeon with valuable knowledge regarding the septocutaneous or musculocutaneous trajectory of the perforator from the source vessel to the skin, as the flexor hallucis longus, soleus, lateral compartment musculature, and posterior crural septum are all easily identifiable on the CTA images. Once the visualized portions of the cutaneous perforator have been traced, the CTA data and the positional

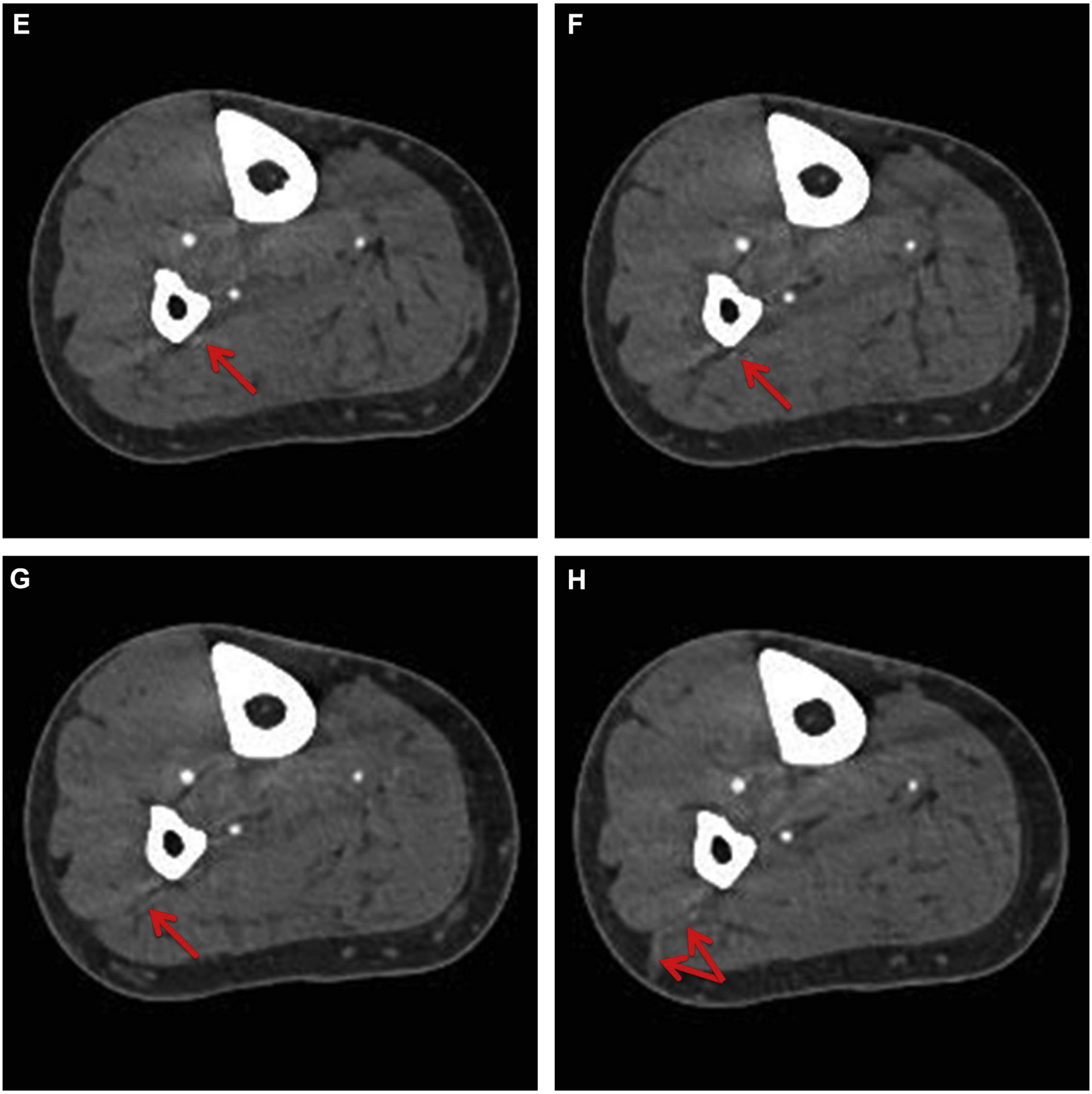

FIGURE 1 (cont'd).

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markers are transferred into 3-Matic Version 11.0 (Materialise, Leuven, Belgium) for additional 3D rendering and CAD. Once imported, the biomedical engineer can connect the previously placed markers to generate a linear 3D object corresponding to the mapped course of the perforator, which is then registered to the virtual 3D rendering of the bony anatomy of the lower extremity (Fig 2A). The distance from the lateral malleolus to the level of the perforator as it crosses the posterolateral aspect of the fibula is then measured and recorded to ensure that the appropriate perforator is being targeted during the intraoperative dissection. Once completed, the surgeon and biomedical engineer can begin designing fibular osteotomy segments to suit the anticipated reconstructive needs using ProPlan CMF 2.1 (DePuy Synthes/Materialise, West Chester, PA; Fig 2B). Identification and overlaying of the perforator data enable the surgeon to "centralize" the perforator on the osteotomy segment of interest or, alternatively, "place" the perforator along an area of usable fibula that maximizes residual pedicle length and prevents

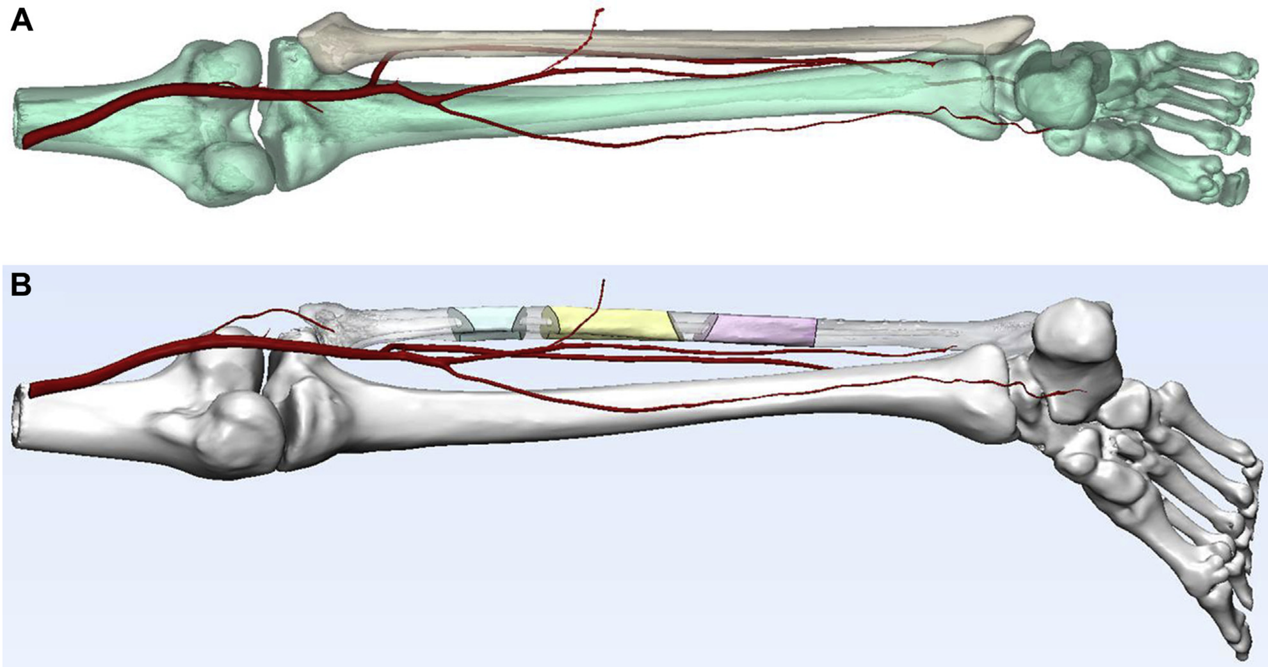

FIGURE 2. Three-dimensional rendering of the perforator trajectory based on the surgeon-directed computed tomographic angiography tracing. *A*, Posterior view displaying the path of the cutaneous perforator as it courses around the posterior aspect of the fibula to supply the skin of the lateral leg (note the oblique course of the perforator from the peroneal take takeoff to its termination in the skin). *B*, Designed fibular osteotomy segments taking into account the cutaneous perforator takeoff and trajectory identified during the surgeon-directed computed tomographic angiography tracing.

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against perforator takeoff directly in the area of a planned osteotomy. This is particularly useful when multiple fibular segments are required for reconstruction and positioning of the perforator along a specific fibular segment is advantageous from a skin paddle insetting standpoint. An index marker also can be designed onto the fibular cutting guide to serve as an additional reference point for correlation with the intraoperative location of the perforator.

Report of Case

A 56-year-old man with a history of right mandibular osteomyelitis and prior segmental resection and fibular free flap reconstruction was evaluated by the Division of Oral and Maxillofacial Surgery at the Mayo Clinic (Rochester, MN) for a new biopsy-proven squamous cell carcinoma arising in the right neomandibular reconstruction bed. The primary tumor arose in the midbody region of the right neomandible, involved the retromolar trigone area posteriorly, and extended to the right parasymphyseal region anteriorly. The tumor was also noted on preoperative Panorex and CT imaging to extend into and erode the underlying neomandibular fibular bone (Fig 3). Accordingly, the patient was planned for a composite segmental mandibulectomy, ipsilateral select neck dissection, osteocutaneous fibular free flap reconstruction from the unoperated right lower extremity, and a tracheostomy for perioperative airway protection. The anticipated surgical defect would require a 3-segment fibular free flap to reconstruct the right mandibular condyle, ramus, body, and parasymphysis in addition to a cutaneous skin paddle for oral cavity relining. A preoperative head and neck CT scan did not identify any pathologic regional adenopathy and preoperative positron-emission tomographic (PET) CT scan did not demonstrate any distant avidity suggestive of metastatic disease. A lower-extremity CTA was obtained to confirm patent 3-vessel runoff in the unoperated right lower extremity. VSP was performed using the CTA perforator localization protocol described above (Figs 1, 2). The plan for the orientation of the fibula was for the vascular pedicle to be directed anteriorly, as the high take-off of a posterior vascular pedicle orientation would preclude reach into the neck for microvascular anastomosis. Based on the need for a 3-segment fibular reconstruction, selection of a perforator that would allow for the skin paddle to be based along the middle fibular segment (the neomandibular body) was clearly the most advantageous design to facilitate soft tissue in-setting at the time of surgery (Fig 2B).

Intraoperatively the fibular free flap was dissected in typical fashion using a lateral anterior approach

FIGURE 3. Preoperative panoramic radiograph depicting an area of saucerized osteolysis involving the proximal segment of the patient's previous right neomandibular fibular free flap reconstruction due to bone erosion from the patient's primary tumor.

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(Fig 4A). A handheld Doppler was used before tourniquet inflation to verify cutaneous perforator location at the level of the skin and to ensure that the skin paddle design was centered on the targeted perforator (Fig 4B). Note that the oblique trajectory of the perforator through the posterior crural septum toward the skin that was identified from the preoperative CTA tracing also was evident in vivo upon skin paddle and fibular elevation (Fig 4A, C). Once the fibula was fully elevated, the patient-specific 3D printed fibular cutting guide was applied to the lateral surface of the fibula and secured in place with multiple monocortical screws (Fig 4C). The fibula was then osteotomized according to the virtually planned segmentation pattern and the anticipated location of the cutaneous perforator relative to the osteotomized segments was noted to be replicated with a high degree of accuracy intraoperatively (Fig 4D). Once the fibula was osteotomized, the pedicle was divided from the leg and the vascular system was irrigated with heparinized saline. The fibula was then oriented and plated using a 3D printed plating tray conceived and collectively designed by the 3 authors (K.S.E., A.E.A., and K.A.; Fig 5). Figure 5 demonstrates the degree of operative fidelity that was achieved in replicating the virtual surgical plan relative to the hard and soft tissue components of the reconstruction. No secondary modifications were required to obtain the relation of the fibular segments shown in Figure 5 and this construct could be transferred directly from the operative table to the surgical field for flap in-setting and completion of microvascular anastomosis.

The Mayo Clinic does not require institutional review board approval for nonsystematic investigations, including technical notes and case reports.

Discussion

The primary purpose of this manuscript was to introduce or further familiarize existing head and neck reconstructive surgeons with a new technique of CTA perforator localization that affords numerous advantages for VSP of osteocutaneous fibular free flaps. While we are likely not the only institution to have incorporated this technique into the routine planning of composite fibular free flaps, it is our presumption that many surgeons within the field are also unlikely to be aware of this planning capability within the context of modern VSP for head and neck reconstruction. Although the identification and tracing of the perforator during VSP does extend the length of the planning session slightly, we strongly believe that the knowledge and understanding of the perforator anatomy gained with this technique vastly outweighs any potential drawbacks to lengthening the VPS meeting. The act of localizing the perforators from the CTA data not only provides the surgeon valuable information relative to the septocutaneous or musculocutaneous course of the perforator, but it also alerts the surgeon of any oblique trajectory of the perforator during its takeoff from the peroneal artery to its termination at the level of the skin (as demonstrated by the presented clinical case). Being able to directly visualize the exact location of the perforator takeoff from the peroneal artery also

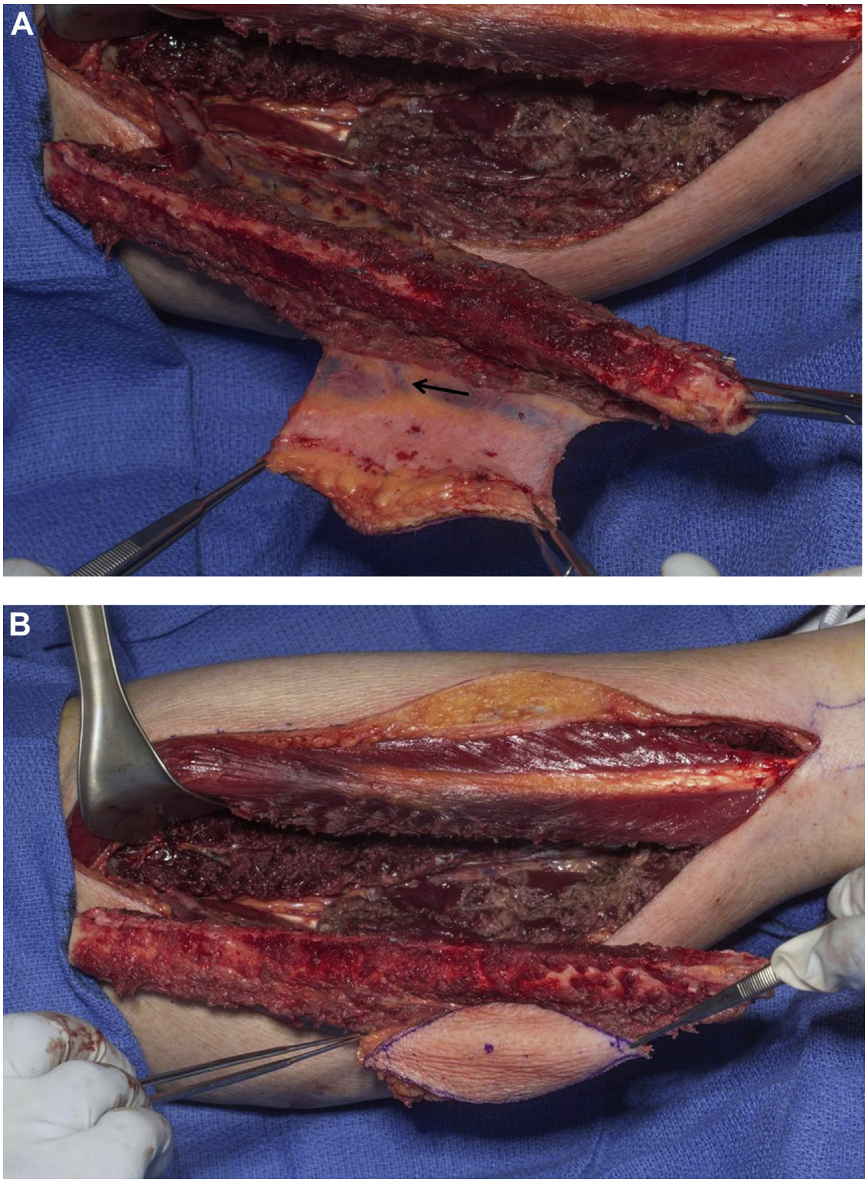

FIGURE 4. Intraoperative dissection of the right fibular free flap. *A*, Elevated fibular bone and skin paddle. Note the oblique course of the perforator through the posterior crural septum toward the skin (*black arrow*). *B*, *Blue marking* on the skin paddle corresponding to the intraoperative transcutaneous handheld Doppler verification of the perforator. **(Fig 4 continued on next page.)**

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enables the surgeon to plan the fibular segmentation in a manner that prevents the perforator position from directly coinciding with a planned osteotomy site. This not only minimizes the chances of perforator damage during manipulation for segmentation of the fibula, but it also increases the likelihood of maintaining surgical accuracy when executing a virtual surgical plan intraoperatively. The latter is particularly true for multisegment reconstructions, when multiple fibular skin paddles are required, when patient-specific fibular cutting guides are employed, and in cases in which custom titanium plates are utilized as any translation or alteration in the cutting guide position along the fibula will ultimately affect the overall accuracy of the final reconstructive construct. Undoubtedly, a factor that most frequently leads to intraoperative modification of virtually planned osteocutaneous fibular free flaps is the preoperatively unknown position of the cutaneous perforators. However, with the described CTA perforator localization technique cutaneous perforator anatomy can now be directly incorporated into preoperative VSP workflows and accounted for with a high level of accuracy within the virtual surgical plan.

Historically, preoperative duplex ultrasound or handheld Doppler mapping was the only way for surgeons to identify potential perforator locations on the

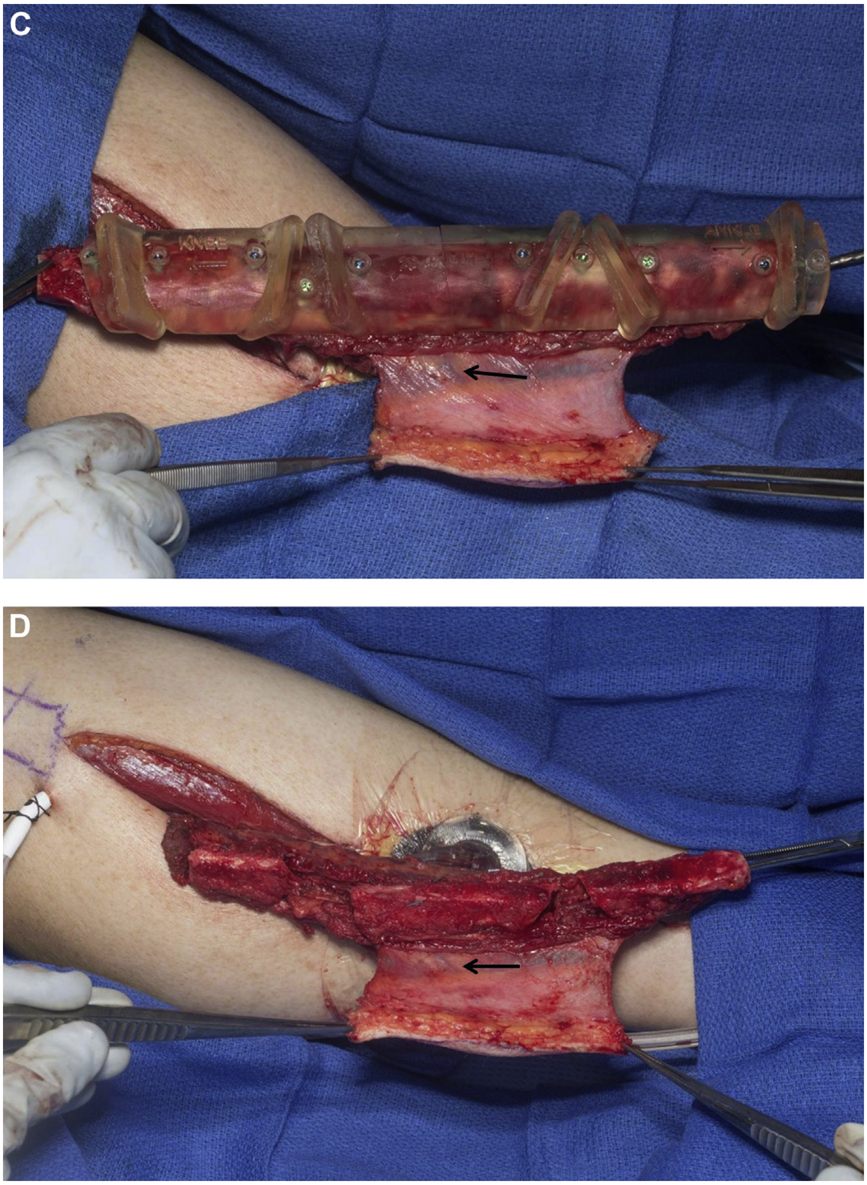

FIGURE 4 (cont'd). *C*, Application of the custom 3-dimensional printed patient-specific fibula cutting guide with the highlighted location of the perforator relative to the central fibular segment (*black arrow*). *D*, Fully osteotomized fibula before harvest from the leg with the perforator location in the posterior crural septum highlighted (*black arrow*).

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lateral aspect of the leg before undertaking an intraoperative dissection. Although Doppler ultrasound can aid in localization of perforators at the level of the skin, it does not reliably provide any information relative to the septocutaneous or musculocutaneous course of the perforator from the underlying peroneal artery.[25-27] In addition, duplex ultrasound mapping is incapable of alerting surgeons of a potentially aberrant perforator origin from other dominant source vessels within the leg, as cutaneous perforator takeoffs from the anterior tibial artery and the posterior tibial artery to the lateral have both been previously described.[28-31] In light of these considerations, many reconstructive surgeons do not use any form of preoperative perforator mapping before osteocutaneous fibular free flap elevation and instead rely only on the intraoperative dissection for perforator identification. Although certainly a tried-and-true method of ensuring appropriate skin paddle positioning relative to the underlying perforator, in the context of VSP, the lack of preoperative perforator knowledge can detrimentally affect the accurate execution of a virtual surgical plan in the operating room—particularly if the perforator location does not coincide favorably with the planned region of the fibula being used for the reconstruction. It is this

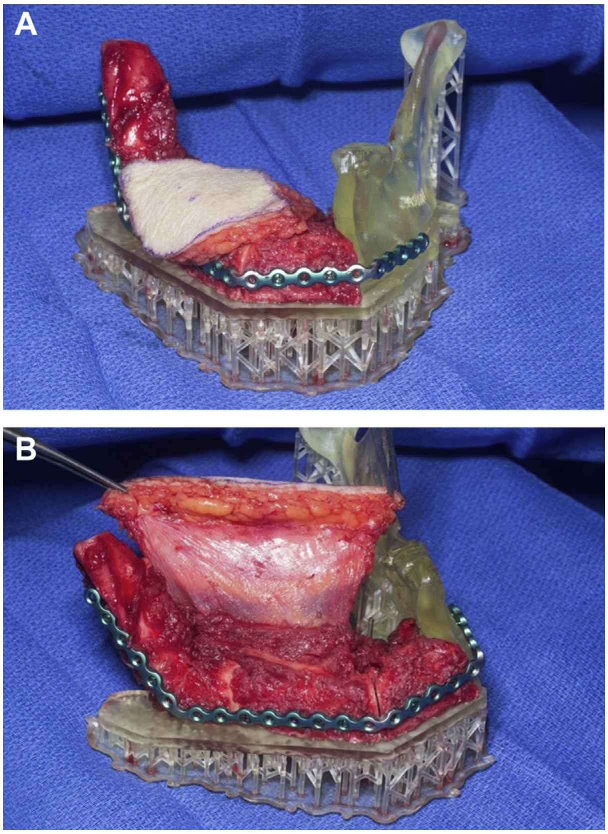

FIGURE 5. Plated fibula on a custom 3-dimensional printed patient-specific plating tray before in-setting. *A*, Anterior view with skin paddle draped in the natural in-setting position. *B*, Oblique view with skin paddle elevated to display the precision of fit of the fibular segments without the need for any secondary modifications to the fibular osteotomies.

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very complication that has led some surgeons to question the routine implementation of VSP technology for planning of osteocutaneous fibular free flaps.[10] However, with the CTA perforator localization method, surgeons can directly account for the cutaneous perforator's location, its septocutaneous or musculocutaneous course, and identify a potentially aberrant takeoff from an alternative source vessel—all during the preoperative VSP session.

At the time of this manuscripts preparation, only 2 previously published studies have specifically reported on the incorporation of preoperative perforator localization into VSP for osteocutaneous fibular free flaps. The first study, published by Berrone et al,[32] reported on a case series of 6 consecutive patients undergoing composite osteocutaneous fibular free flap reconstruction for oral cavity squamous cell carcinomas. They used a hybrid technique of correlating perforator location based on pre-VSP clinical handheld Doppler mapping of perforator locations relative to the lateral malleolus of the leg. These measurements were then transferred to the VSP rendering of the fibula and osteotomies were designed to centralize the location of the handheld Doppler position along the desired fibular segment. In 4 of the 6 cases reported by Berrone et al,[32] they noted good correlation between the position of the perforating vessels localized by handheld Doppler measurement and the bone segment being used for reconstruction. However, they did not provide specific information regarding the 2 cases in which the perforator locations and the fibular segments did not coincide favorably. Berrone et al[32] commented in their discussion that surgeons must be prepared for the often imprecise concordance between handheld Doppler measurements of cutaneous perforator locations and the actual perforator locations identified from direct visualization during operative dissection.

The second and more recent study reporting on perforator localization for VSP of osteocutaneous fibular free flaps was published just before finalization of the present report. In this study, Battaglia et al[33] reported on a series of 20 patients undergoing head and neck reconstruction with osteocutaneous fibular free flap for benign or malignant head and neck tumors at a single institution. Analogous to the techniques reported in the present manuscript, they identified perforator locations purely based on preoperative CTA imaging. Battaglia et al[33] also used the lateral prominence of the lateral malleolus as an external reference point from which to measure the location of the perforator identified on the CTA images. They measured the distance from the midpoint of the lateral malleolus to a subcutaneous position of the perforator based on the CTA images. Once the perforator was identified intraoperatively, Battaglia et al[33] cross-referenced the intraoperative perforator locations with the preoperative virtual measurements obtained from the CTA images. They report an average distance between the CTA perforator locations and intraoperative perforator locations for their cohort of 20 patients to be 1 mm (range, 0 to 2 mm). Battaglia et al[33] concluded that preoperative CTA evaluation to investigate lower-extremity vascular patterns for patients undergoing composite osteocutaneous fibular free flaps is a valuable approach for decreasing complications arising from variable vascular anatomy for VSP, but that additional follow-up studies would be required to evaluate the long-term outcomes and advantages of this contemporary technique.

Undoubtedly, the application of VSP to head and neck microvascular reconstructive surgery still remains in its infancy, as its various technical shortcomings and inadequacies are only becoming more fully elucidated through the increasing level of acceptance of the technology among providers. Currently, there is a relative paucity of high-level evidence from which surgeons can objectively weigh the merits and drawbacks of VSP technology for applications in complex head and neck reconstruction, yet the body of evidence investigating the benefits of VSP is slowly beginning to grow. Given the clear need for further systematic analysis of nuanced techniques unique to VSP for head and neck reconstruction, we are currently in the process of prospectively collecting data in a multi-institutional fashion on the accuracy and reliability of the CTA perforator localization method described above. It is our hope that with further investigation of this technique that CTA acquisition protocols and existing VSP workflows can be modified in a universal fashion to allow for more rapid and accurate presurgical modeling of cutaneous perforator anatomy and enable all surgeons using VSP for head and neck reconstruction to begin incorporating this technique into their daily practice. Although it remains true that current VSP technology cannot yet fully encompass the entire breadth of reconstructive considerations that a surgeon must make when planning a head and neck free tissue transfer, ongoing innovation within the field will likely continue to push this technology toward a future in which more comprehensive modeling of head and neck reconstructive procedures can eventually become a reality. In this light, we have continued to find great utility in the routine use of the CTA perforator localization method during VSP for osteocutaneous fibular free flaps. It is our hope that through this report other surgeons will begin to immediately enjoy from the numerous benefit of applying this technique as well.

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