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Planning and optimising DIEP flaps with virtual surgery: the Navarra experience

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Summary Methods to improve operative outcomes in deep inferior epigastric artery perforator flap surgery have previously focussed on operative technique and postoperative-course modification. Recently, preoperative imaging has become capable of mapping the entire course of perforating vessels, including those vessels as small as 0.3 mm, enabling 'virtual surgery' to be performed preoperatively. This has been shown to facilitate faster and safer surgery. The recent 'Navarra' meeting classified current imaging modalities and discussed the current status of imaging modalities for this role. This article discusses the current expectations and optimal techniques for achieving these outcomes through the available imaging modalities: Doppler ultrasound, colour Doppler (duplex) ultrasound, computed tomography angiography (CTA) and magnetic resonance angiography (MRA). Features of imaging that are of importance to the surgeon are explored, and a consensus statement has been developed that describes exactly what the current imaging modalities should aim to deliver to the surgeon prior to operating, as well as the benefits and pitfalls of each of these modalities. The techniques described herein permit the radiologist and the surgeon to perform virtual surgery together, preoperatively.

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The improvement in outcomes from autologous breast reconstruction has become increasingly sought after and discussed in the international literature.^{1–9} With this in mind, an open meeting of international groups performing deep inferior epigastric artery perforator (DIEP) flaps with the use of preoperative imaging took place in Pamplona, in the Navarra region of Spain, on 19 April 2008. In an open forum, discussion of all available imaging modalities for perforator mapping was undertaken, with a view towards improving and standardising current techniques, sharing knowledge and providing a framework for future advances in this rapidly advancing field of technology.

Previous attempts at improving outcomes for DIEP flaps have largely focussed on operative technique and post-operative-course modification.^{3,8} This forum, however, focussed on being able to plan DIEP-flap surgery from beginning to end, before the operation has even begun. Indeed, 'virtual surgery' was the catch-cry of the day. With the use of technologies currently available and in usage, surgeons can now select the appropriate patient, the hemiabdomen of choice, the individual perforator(s) of choice, design the flap and, indeed, the volume of the flap and can both predict and plan the anastomoses required for supply and drainage of the flap.

The current expectations and optimal techniques for achieving these outcomes are discussed in this article, with a consensus statement which was developed that describes exactly what current imaging modalities should aim to deliver to the surgeon prior to operating. The techniques described herein permit the radiologist and surgeon to perform virtual surgery together, preoperatively. The combined experiences of the authors, with over 400 DIEP flaps performed with the use of preoperative computed tomography angiography (CTA), suggest that undertaking preoperative perforator flap virtual surgery can significantly reduce operative time in the number of hours and can maximise operative success in terms of flap survival and donor-site morbidity.

The vascular anatomy of DIEP flaps: optimising supply

Two major philosophies in the raising of a DIEP flap were evident, which required consideration when forming standards in preoperative imaging. Some groups routinely use a single perforator as the sole supply to the DIEP flap. These surgeons describe using only one perforator in up to 90% of the cases, with only the infrequent inclusion of a second perforator. Other groups describe the routine use of two or more perforators, with only the infrequent use of a single perforator (less than 20% of cases). These fundamental differences in philosophy become important when considering the needs of preoperative imaging. When only a single perforator is likely to be used, the transverse intramuscular course is of little concern, as separation of muscle fibres precludes the need for muscle sacrifice. On the other hand, if two or more perforators are used, the transverse course of the perforators necessitates the dissection of the muscle intervening between the two perforators, and thus preoperative awareness of the transverse course is essential.

With these two techniques in mind, an evaluation of the most favourable anatomy for a DIEP flap can be discussed.

From pedicle to skin, the blood supply to the flap can be classified as having varying segments: the deep inferior epigastric artery (DIEA) course deep to the rectus abdominis muscle, the intramuscular course of the DIEA, the intramuscular course of the DIEA perforator, the per fascial course of the perforator and the subcutaneous course of the perforator. The 'ideal' vascular pedicle can thus be described in terms of these segments:

- 1) large-calibre DIEA and vascular pedicle;
- 2) large-calibre perforator (both artery and veins);
- 3) central location within the flap;
- 4) short intramuscular course;
- 5) perforating veins communicate with the superficial venous network;
- 6) broad subcutaneous branching, particularly into the flap;
- 7) longer subfascial course and
- 8) avoids tendinous intersections.

These factors were chosen based upon maximising the ease and speed of operation and the clinical experience of complication in DIEP-flap surgery. The size of the DIEA pedicle and perforator is intuitive, in terms of optimising supply to the flap. Centrality of the perforator similarly maximises the supply to the peripheral parts of the flap. A short intramuscular course has several benefits. In all cases, a short, longitudinal, intramuscular course is associated with ease and speed of dissection and the likelihood of less muscular branches requiring ligation. In the case of more than one perforator being included in the flap, a short transverse distance is associated with reduced dissection time and a reduced need for muscle sacrifice. The fifth factor, that of a perforating vein that communicates with the superficial system of veins, is based on the broad experience that venous congestion is one of the more significant sequelae of DIEP flaps, and, in fact, there was general consensus that evaluation of the venous anatomy was just as, or more, important than evaluation of the arterial supply. This frequent observation was described where venous congestion occurred in cases where there was preferential superficial venous drainage of the flap and that wherever a communication between the deep and superficial venous systems was evident on preoperative angiography, problems with venous drainage were less likely to occur. A broad subcutaneous segment and ramification of perforators into the flap improved flap vascularity and flap design. A long subfascial segment was sought, as this was associated with a reduced intramuscular course, and tendinous intersections were avoided, as these were associated with difficult dissections. Of all of these factors, the last two factors were considered the least important for perforator selection, although still worthy of consideration.

Evaluation of these eight factors on preoperative imaging was thus considered essential to operative planning.

Requirements of preoperative imaging

With formal classification of the vascular anatomy of DIEP flaps and the requirements for optimal supply in DIEP flaps, the means to identifying these factors preoperatively can

thus be determined. Optimally, the surgeon and radiologist will together interpret the imaging data in a three-dimensional format and, it is in this way, by following the pedicle from its origin and through the soft tissues, that virtual surgery is indeed performed. Regardless, certain images are worth capturing in two dimensions for reference at subsequent stages, and these are:

Location maps

Two anterior views of the abdominal wall are preferred that demonstrate the location of perforators at the plane at which they emerge from the rectus sheath. Of these two views, the first should include a view that demonstrates the relative size of the perforators (with the locations shown) (see Figure 1), and the second view should demonstrate the DIEA and its main branching pattern (with the location of perforators superimposed) (see Figure 2). It is with these two views that the relative size of perforators and the location of perforators relative to their source vessels can be clearly seen.

It is noteworthy that this method of localisation has been routinely achieved with arrowheads, and different colours have been assigned to varying sizes. This need not be the only method, but certainly has been used with success among all groups. The routine point of reference for localisation has been the umbilicus, and this has been achieved with success; however, other methods, such as skin-attached markers, have also been used successfully.

DIEA pedicle

A view of the DIEA pedicle and its branching pattern is essential in order to plan the branch of choice for inclusion as the vascular pedicle, as well as to estimate its calibre. This is usually achieved in one of the location maps; but, where this is not possible, a separate image may be required (Figure 2).

Intramuscular course

The intramuscular course is highly important and needs to be demonstrated with imaging. As discussed earlier, the longitudinal transverse distance is important in all cases as a means to predicting the extent of intramuscular dissection. This is best demonstrated with a curved, longitudinal maximum intensity projection (MIP) view on CTA and MRA reconstructions (see Figure 3).

The transverse distance is not highly important in the situation where a single perforator is used in the raising of a DIEP flap, and thus a view demonstrating this transverse course is not routinely required for some institutions. However, for institutions where multiple perforators are routinely selected for the supply to flaps, visualisation of the transverse intramuscular distance is highly important. This is best demonstrated with axial MIP views on CTA and MRA reconstructions (see Figure 4).

Superficial Inferior Epigastric Artery (SIEA) and Vein (SIEV)

The views of the SIEA and SIEV are important for consideration of raising an SIEA flap. An SIEA is only present with

a calibre sufficient to raise an SIEA flap in up to 30% of patients, and this may certainly be predicted on preoperative imaging^{10–12} (see Figure 5). Many surgeons routinely identify and preserve the SIEA intra-operatively for use as the major vascular pedicle or for preservation if the need for vascular augmentation is required.

More significantly, evaluation of the SIEV is highly important for predicting and planning the venous drainage of the flap, particularly as the SIEV and SIEA usually enter the abdominal-wall pannus considerably distant from each other. Few authors would dispute that venous congestion is one of the more significant flap-related complications of DIEP flaps, and evaluation of the venous drainage on preoperative imaging is thus highly important.

Superficial Inferior Epigastric Vein (SIEV) to perforator communication

An additional component of evaluation of the SIEV is its communication with the deep inferior epigastric vein (DIEV). A study by Blondeel et al.¹³ demonstrated that a large SIEV system was a predictor of preferential superficial drainage, and thus of inadequate venous drainage of the flap when only the DIEV was used in the flap. More recent experience with preoperative imaging, at least anecdotally, has suggested that if perforating veins are clearly visualised as communicating with the SIEV, then adequate venous drainage can be predicted (see Figure 6).

We suggest, *per se*, that a clear demonstration of this communication with the selected perforator(s) be demonstrated. In the case of CTA or MRA, this view is best achieved with a sagittal/oblique volume-rendered technique (VRT) reconstruction, with the skin cropped (removed).

Abdominal-wall competence and contour

Often incorporated into one of the perforator-location maps, a view and evaluation of the deep fascial layers of the abdominal wall are required. This should include evaluation of the width and competence of the linea alba (for divarication of recti), assessment for any other scars or hernias and an assessment of the thickness of rectus abdominis muscle (Figure 7). These factors can all help to predict abdominal-wall complications and the need for greater attention to abdominal-wall closure.

Current modalities for preoperative imaging

The Doppler probe

Since its introduction into widespread use for perforator mapping in 1990,¹⁴ the hand-held, unidirectional Doppler probe has remained the cornerstone of preoperative imaging. The Doppler probe is cheap and quick, easily applied by the surgeon and can be directly applied compared to postoperative Doppler findings.^{14,15} Even in the age of advancing technologies in imaging, the Doppler probe continues to be used as adjunct to other methods. Formal perforator mapping with Doppler alone has not been widely considered as sufficient for perforator mapping and certainly cannot achieve the sensitivity and breadth of

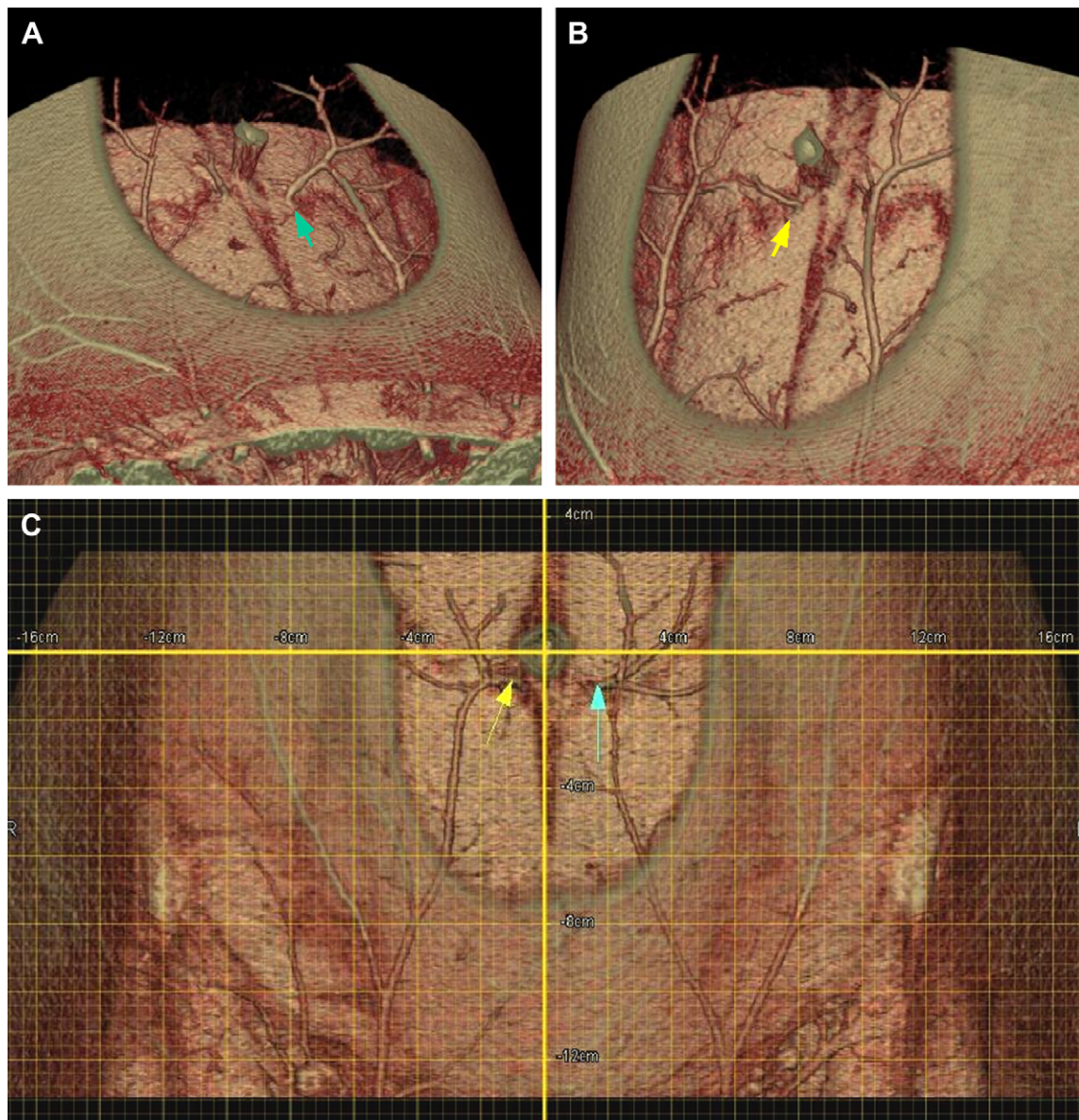


Figure 1 Computed tomography angiogram (CTA) images with volume-rendered technique (VRT) reformats, showing oblique-coronal (Figure 1A and B) and coronal view (Figure 1C). The largest perforator vessels are demonstrated, as is the exact point at which they pierce the rectus sheath (see arrows in Figure 1A and B). With the aid of a grid, centred at a standardised central position (umbilicus), the perforator vessels are located in the coronal VR view (arrows in Figure 1C).

information sought with current technologies.^{16–19} In addition, with significant time associated with perforator mapping, low accuracy and high interobserver variability, unidirectional Doppler is not currently embraced as a suitable preoperative imaging modality.

Colour Doppler/Duplex ultrasonography

The use of two-dimensional colour Doppler has shown a significant improvement on unidirectional Doppler and has been widely used for perforator mapping. Although it maintains a significant degree of false positives and false negatives, it is freely available and cheap to perform. It does maintain high scanning times and interobserver variability and does not achieve many of the features of

perforator mapping sought with the current technologies, as described in this article.^{15,17–19}

Multislice CTA

CTA is currently considered, both in the literature and among current practitioners, as the gold standard in preoperative imaging for DIEP flaps. It can achieve all of the requirements for perforator mapping as described in this article and can do so with high accuracy, low cost and low interobserver variability.^{18,20–25} These studies have shown CTA to be significantly more accurate than other imaging modalities, for both perforator mapping and demonstrating all the other vascular characteristics sought. Its main limitation is the availability of the machine itself and the

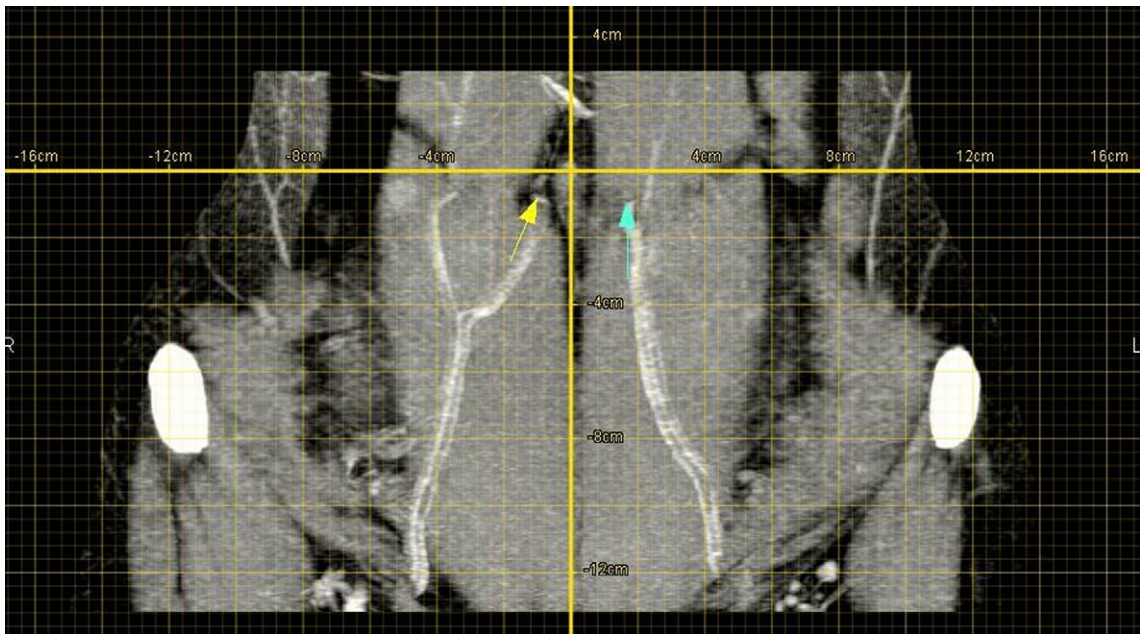


Figure 2 Computed tomography angiogram (CTA) image with coronal maximum intensity projection (MIP) reformat, demonstrating the branching pattern of the deep inferior epigastric artery and vein in each hemiabdominal wall. The location of the largest perforator vessels can be demonstrated with this image.

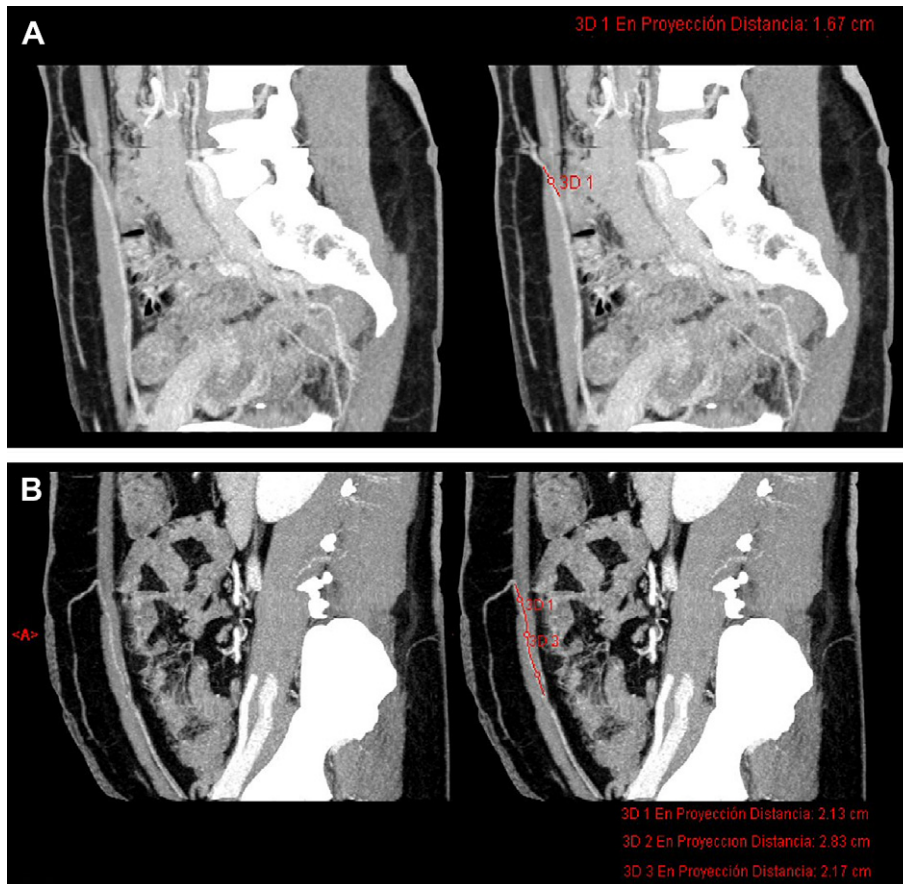


Figure 3 Computed tomography angiogram (CTA) images with curved maximum intensity projection (MIP) reformats, demonstrating the longitudinal intramuscular course of the main perforator vessels. **Figure 3A** shows an example of a perforator with a short intramuscular course and a direct fascial penetration pattern. Measurements of the intramuscular distance traversed are shown on the right. **Figure 3B** shows a long intramuscular course and a direct fascial penetration pattern, with the measurements shown on the right.

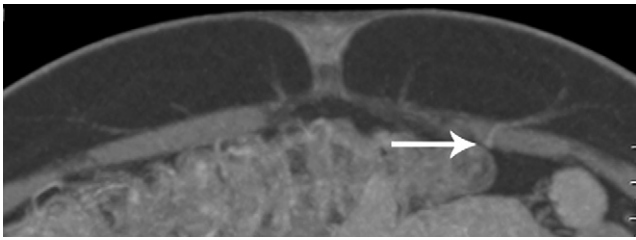


Figure 4 Computed tomography angiogram (CTA) images with axial maximum intensity projection (MIP) reformats, demonstrating the transverse intramuscular course of the main perforator vessel (arrow).

associated software, although this is not an issue for most institutions, and all authors have achieved high-quality images with a wide range of multidetector row scanners (from four slice to 64 slice). The only relative contraindications for the use of CT is severe claustrophobia (although scan times are but a few seconds), a sensitivity to the intravenous contrast or renal impairment.

The scanning protocols are worthy of discussion, as two modes of scanning were described. Both methods used a bolus-tracking technique to identify filling of the appropriate vessels with contrast as a means to initiate scanning. The first technique, after identifying contrast filling, used an extensive delay before scanning, creating a venous-phase scan, which was able to achieve maximal filling of both arterial perforators and veins. When using a four-row multislice scanner, this equated to a 30-s delay, and when using a 64-row scanner, a 50-s delay was used. The benefit

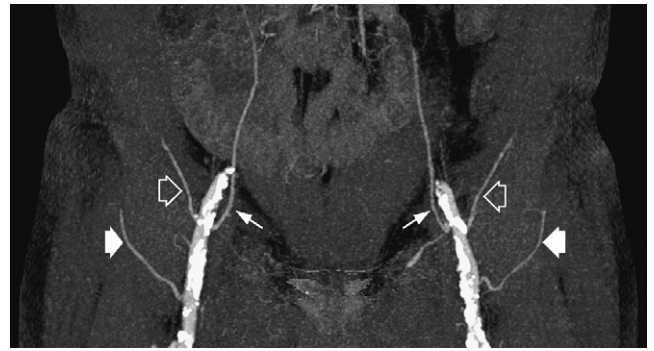


Figure 5 Computed tomography angiogram (CTA) volume rendered technique (VRT) reformat demonstrating the origin and course of the superficial circumflex iliac arteries (large filled arrows) in a patient with absent superficial inferior epigastric arteries. The deep circumflex iliac arteries (large hollow arrows) and deep inferior epigastric arteries (small filled arrows) are also shown.

of this technique is a thorough examination of both arteries and veins, which is essential to complete preoperative planning. Although the DIEA and DIEV can be readily differentiated, the downside of such an approach is that there is very little ability to differentiate between the perforating arteries and veins, and thus there is a risk of confounders. Similarly, the SIEA is difficult to assess with this method, both due to confounding by the SIEVs and by some inadequacy in filling by the timing of the scan. The second method of scanning does not use any delay in

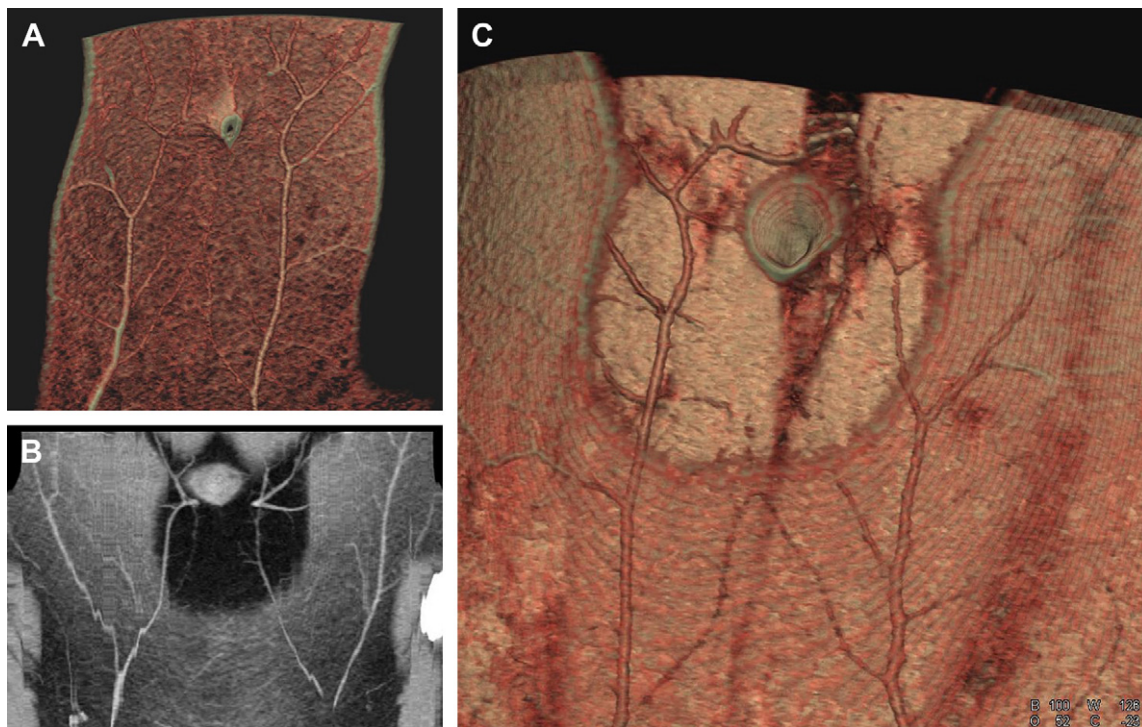


Figure 6 Computed tomography angiogram (CTA) images with volume-rendered technique (VRT) reformats, demonstrating the superficial venous drainage system (Figure 6A and B). The cutaneous anastomosis between the superficial veins and the largest perforator vessels are shown (Figure 6C).



Figure 7 Computed tomography angiogram (CTA) images with volume-rendered technique (VRT) reformats, in which rectus abdominis diastasis can be evaluated (arrows).

scanning after the contrast reaches the appropriate vessels, limited only by the minimal delay of the particular scanner (approximately 4 s). This is, therefore, a pure 'arterial-phase' scan, which provides a presumed improved accuracy for perforating artery mapping and for demonstrating the SIEA; however, it lacks any strong appreciation of the venous system.

An additional feature of the scanning discussed was the range or extent of scanning. Most institutions limited the scan range to the origin of the DIEA and SIEA on the common femoral as the lower limit of the scan, with the superior limit of the scan kept to the upper extent of the flap (between 2 and 4 cm above the umbilicus). Similarly, CTA imaging of the internal mammary recipient vessels was a point of contention (Figure 8). It was widely considered that CTA of these vessels was not required for several reasons. First, if patients have had any previous thoracic imaging with CT, these vessels can be well evaluated on these scans. Furthermore, ultrasonography is frequently available and is usually sufficient to identify and describe these vessels. However, where neither of these modalities is available, CTA may be an alternative option.

Three-dimensional reconstructions are essential in order to achieve the images discussed previously. These are achieved using computer software that performs multi-planar reconstructions. Volume-rendered technique (VRT) and maximum-intensity projection (MIP) reconstructions are widely used for this purpose and can be achieved with a wide variety of software programs from many software companies.²⁶ MIP reconstructions are optimal for demonstrating the DIEA pedicles and the intramuscular course of perforators. VRT reconstructions assign colour to data points which display a two-dimensional representation of the three-dimensional data set, and are thus useful for representing the subcutaneous course of perforators and for generating perforator-location maps.



Figure 8 Computed tomography angiogram (CTA) images with volume-rendered technique (VRT) reformats, in which the internal mammary vessels can be evaluated (arrows).

A limitation of CTA remains the radiation exposure associated with its use. The radiation dose has been widely discussed and, although worthy of consideration, is not as significant as may have been initially thought. Studies of the radiation dosage have been performed across institutions, and when limited to the scanning range described above, the radiation dose is less than 6 mSV, which is considerably less than a standard abdominal CT scan and is the dose associated with four abdominal plain films (ImpACT CT Patient Dosimetry Calculator Version 0.99w, ImpACT, St. George's Hospital, London, UK).^{18,24} With the benefits of scanning as considerable as they are, few would be concerned by this degree of radiation exposure. However, limiting the scanning range is still important, and if a full chest and abdominal CTA was to be performed, this would increase radiation exposure to almost 3 times the dose.

MRA

An MRI, without intravenous contrast, has been attempted in the past but with inadequate results for perforator mapping.²⁷ With more recent exploration into the role of MRA, the prospect of using MRA for perforator mapping is now a realistic prospect. MRA is currently being trialed in several centres by some of the current authors, and the results are certainly very optimistic. The expectations outlined in this article for preoperative imaging are all achieved by MRA, but not currently established to the degree that CTA can. Current modifications to the technique include differing contrast media, scanning techniques and the use of digital subtraction reconstructions. It is expected that in the coming months, MRA may well rival CTA for the quality of imaging required for perforator mapping. The benefit of MRA lies in the lack of ionising radiation, but has the problem of expense, availability and the length of scanning times.

Discussion

The benefits of preoperative imaging have moved from the realm of possibility to proven outcomes. All of the current authors have shown that even amongst different institutions, with different surgeons and radiologists, outcomes

can be improved with the use of advanced imaging technologies performed preoperatively. Patients with unfavourable anatomy can be selected out prospectively, the hemiabdomen of choice and perforator of choice can be chosen preoperatively to save operative time and the perforators which maximise the vascularity of the flap while minimising rectus abdominis-muscle damage can be selected. Of particular benefit is the ability to modify operative technique on the basis of preoperative imaging, in being able to select between a transverse rectus abdominis myocutaneous (TRAM), DIEP or SIEA flap.^{28,29} In fact, all outcome measures have been shown to be improved in patients undergoing preoperative imaging, with statistically significant findings demonstrated for a reduction in flap-related complications (flap loss and fat necrosis), donor-site complications (abdominal-wall weakness and bulge) and intra-operative surgical stress.²⁸ These findings were all shown with the use of CTA and have not yet been demonstrated for the other modalities.

In addition to the proven outcome measures, CTA has been shown to be the most accurate modality for perforator mapping, with a sensitivity and positive predictive value of 100% in cadaveric studies,³⁰ and a sensitivity and positive predictive value of 99.6% in clinical studies.³¹ Ultrasound, as discussed, has been shown to be inaccurate, while MRA has not yet been trialled for this purpose.

The financial cost, a pertinent issue in any health system, is complex and has not yet been evaluated. The cost of the imaging alone is variable, but is in the order of US\$250 for a Duplex ultrasound, US\$400 for a CTA and US\$600 for an MRA. However, these costs are only significant when discussed in the context of cost savings from the reduction in operating time and length of stay, all shown to be reduced with the use of CTA.²⁸

Conclusion

Preoperative planning is an essential element of DIEP-flap surgery. Adequate imaging can aid patient selection, plan the operative technique, reduce operating time and improve operative outcomes. The features identified by the authors and discussed in this article are sought from current imaging modalities, and highlight the key assessment tools to be applied to emerging imaging techniques.

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