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Preoperative Imaging for Perforator Flaps in Reconstructive Surgery

A Systematic Review of the Evidence for Current Techniques

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Background: Although preoperative imaging of perforator vasculature in planning microvascular reconstruction is commonplace, there has not been any clear demonstration of the evidence for this practice, or data comparing the many available modalities in an evidence-based approach. This article aims to provide an objective, evidence-based review of the literature on this subject.

Methods: The evidence supporting the use of various modalities of imaging was investigated by performing focused searches of the PubMed and Medline databases. The articles were ranked according to the criteria set out in March 2009 Oxford Centre for Evidence-Based Medicine definitions. Endpoints comprised objective outcome data supporting the use of imaging, including flap loss, unplanned returns to theater, operative time reduction, and surgeon-reported stress.

Results: The objective high level of evidence for any form of preoperative perforator imaging is low with only small number of comparative studies or case series investigating computed tomographic angiography (CTA), magnetic resonance angiography, handheld Doppler, color duplex, and classic angiography. Of all modalities, there is a growing body of level 2b evidence supporting the use of CTA.

Conclusion: While further multicenter trials testing hard outcomes are needed to conclusively validate preoperative imaging in reconstructive surgery, sufficient evidence exists to demonstrate that preoperative imaging can statistically improve outcomes, and that CTA is the current gold standard for perforator mapping.

Key Words: free flap, perforator flap, reconstructive surgery, imaging, CTA

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Preoperative imaging to assess the vasculature has been of interest to reconstructive surgeons since the earliest days of microsurgical reconstruction. At that time, all microsurgery was considered "cutting edge" and the imaging modality most often used was the handheld Doppler probe. Presently, increasingly technically demanding flaps based on perforator vessels mean many surgeons consider it more important than ever to assess the perforator vasculature as part of the preoperative workup. Free flap surgery has become increasingly successful over the past 30 years; however, there remains a failure rate of 2% to 4%, and this is possibly higher in the subgroup comprising perforator-based free flaps.

Flap failures and partial necrosis in technically successful operations may be attributed to interindividual variations in perforator anatomy. These could be congenital or acquired secondary to previous trauma, surgical, or otherwise. In this setting, it is hypothesized that some form of preoperative perforator mapping would alert the surgeon to the anomalous anatomy and steer the choice of operation to a safer part of the body or facilitate planning. This is particularly pertinent in the modern era due to the significantly higher variability of perforator systems than their parent axial vessels. These variations, when detected intraoperatively can lead to impromptu changes of plan that can further prolong operative times, anesthetic times, increase surgeon fatigue, and possibly contribute to poorer outcomes.

Almost all available imaging modalities have been proposed for the preoperative assessment of vessels in microvascular reconstructive cases. These include the handheld Doppler, color Doppler duplex ultrasound scanning, traditional angiography, computed tomographic angiography (CTA), magnetic resonance imaging and angiography (MRI/A), and even stereotactic guidance systems as used in neurosurgery. Some of these modalities have been adopted by units around the world as a routine part of the workup, whereas many believe that no systematic imaging is required before surgery. These strategies appear to be ad hoc, and there is a general lack of consensus on whether imaging is required at all, required in all cases, or in select cases and if so, which imaging modality should be used.

The ideal imaging modality would satisfy a number of key criteria. It would give accurate information about the course and caliber of perforating vessels down to the submillimeter level. It would be reproducible and have low interoperator variability. The imaging technology would be fast, inexpensive, and readily available. There would be a low radiation dose allowing the test to be used in a routine screening capacity. If the scan provided information on incidental comorbidities pertinent to the surgery or the patient's condition as a whole this would be of additional value.[1]

This article seeks to objectively assess all the literature on this subject with a view to contributing toward a consensus position among reconstructive surgeons. An exhaustive search of the literature was performed and the results critically appraised with strict adherence to the criteria issued by the Oxford Centre for Evidence-Based Medicine (freely available at the website http://www.CEBM.net). These broadly state that evidence is ranked categorically, with randomized control trials at the highest level of evidence to expert opinions at the lower level. The grading system allows for studies to be dropped down based on weakness of construction.

The review findings are presented according to modality (see Figs. 1–4), with a subgroup analysis for various different settings such as donor perforator system, recipient vessel identification, and limb reconstruction.

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METHODS

A systematic review of the literature was undertaken, with studies for inclusion identified using the PubMed and Medline databases. Because of the large variation in terms used for many imaging modalities across the world (eg, CT angiography vs. CTA vs. computed tomographic angiography vs. computed tomography angiography) a large number of repeated searches were performed. This was an attempt to address the possible selection bias in using only certain terms and ensure that all relevant studies were found and included. Keyword searches were performed using the terms: "flap," "reconstruction," and "transfer" linked with AND operator to "CTA," "CT angiography," "computed tomographic angiography," "computed tomography angiography," "Doppler," "ultrasound," "duplex," "magnetic," "MRI," "MRA," "angiography," "stereotaxy," "stereotactic." These searches provided a vast number of results (n = 4219) sacrificing specificity for sensitivity. This ensured that whether authors had used the terms "free flap," "microsurgical reconstruction," "free tissue transfer," or any combination or abbreviation thereof, the studies would be included. After the results were returned, they were manually filtered for relevance. This number was further reduced by only including studies in the date range 2000–2010 and only including those studies in English. The resulting 265 studies were assessed and the most relevant ones are presented here, omitting papers with very low levels of evidence such as simple case reports and series. These studies are assessed for gross errors of construction and subsequently attributed a CEBM evidence level (see Fig. 5 and Table 1).

TABLE 1. Current Level of Evidence for Preoperative Imaging Techniques, by Centre for Evidence-Based Medicine (CEBM) Criteria

Preoperative Imaging Technique for Perforator Mapping	Level of Evidence for Efficacy of Technique
Handheld Doppler probe	4
Color Doppler/duplex ultrasound (Eco-Color Doppler)	4
Catheter angiography/digital subtraction angiography	4
Computed tomographic angiography (CTA)	
°Abdominal wall flaps	2b
°Other body regions	4
Magnetic resonance angiography (MRA)	
°Abdominal wall flaps	3b
°Other body regions	4
Image-guided stereotaxy	4

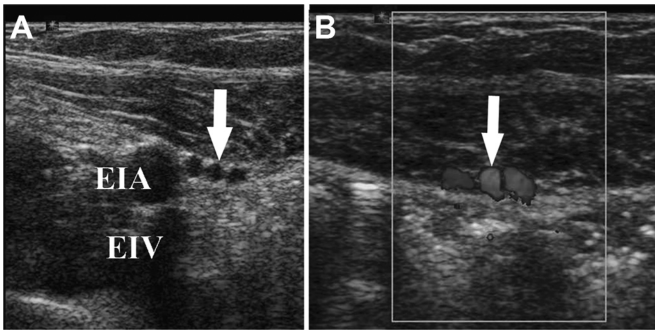

FIGURE 1. Conventional ultrasound (A) and color Duplex ultrasound (B) of the anterior abdominal wall vasculature, with the deep inferior epigastric vessels (arrows in A and B) demonstrated immediately adjacent to the pedicle origin on the external iliac artery (EIA) and vein (EIV).

RESULTS

Doppler Ultrasound

The handheld Doppler ultrasound probe is a relatively inexpensive, portable unit which is readily available in most hospitals. When applied to the skin with an interface layer of ultrasound gel to facilitate transmission, it emits an audible signal when over blood vessels. This sound is loudest if the vessel is pointed directly toward the probe. Handheld units are typically available in 8 and 10 MHz versions. This device was advocated for use in planning microvascular free flaps as early as 1975[2,3] and was a common practice by 1990.[4] The handheld Doppler has been mainly described for assisting in identifying donor vessels before surgery. Many studies have shown the Doppler probe to have reasonable accuracy in identifying perforators in preparation for various free-flap operations,[4–7] although some of them report worrying inaccuracies when compared with operative findings, especially in smaller, deeper vessels[8,9] and a number of comparative studies have found the technique to be less accurate and suffer higher interuser variation when compared with newer modalities such as CTA.[10]

No control studies exist and neither do any studies showing improved outcomes such as shorter operating times or improved flap survival. For this reason, the highest level of evidence supporting the use of preoperative Doppler ultrasound is level 4 (Table 1). Despite its drawbacks, Doppler continues to be popular, possibly because of its widespread availability. Recent reported uses of Doppler include planning pedicled flaps based on perforators[11,12] and in the emerging field of so called "free style" perforator flaps.[13–16]

Color Duplex Ultrasound (Eco-Color Doppler)

Color duplex ultrasound (frequently referred to in the literature as "color Doppler") uses ultrasound to produce a grayscale image on a screen. This traditional ultrasound image is augmented by the color identifying movement, in this case blood flow. Fast flowing blood can be distinguished from slow flowing thus demonstrating arteries and veins. This technology has been shown to be useful in identifying the position of perforators preoperatively in the setting abdominal flaps,[17–19] gluteal flaps,[20] and of anterolateral thigh (ALT) flaps,[21] and indeed to be more accurate than Doppler ultrasound in this setting.[22] Nonetheless, comparisons with more modern technologies such as CTA showed color duplex to be less accurate, provide less information on the intramuscular course of vessels, slower, and not provide information on other nearby vessels such as the superficial epigastric vessels.[10,23] One comparative study showed comparable accuracy and suggested that the radiation exposure should be taken into account making color duplex favorable over CTA in some cases.[24]

Despite the numerous articles referencing color Doppler sonography as a preoperative imaging modality in the planning of microvascular free flaps, no control studies exist demonstrating improved outcomes, decreased operative time, or any other end point. Consequently, the highest level of evidence assignable to this imaging modality is level 4 (Table 1).

Catheter Angiography

Classic arterial catheter angiography and its modern day extension—digital subtraction angiography have been advocated for preoperative imaging since the early days of microvascular reconstructive surgery. This has predominantly been in the limbs, particularly the lower limb in the context of either reconstruction after

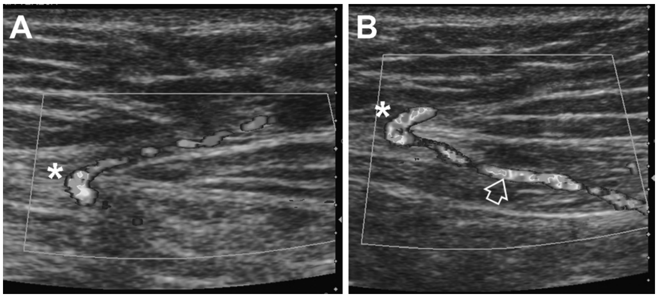

FIGURE 2. Color Duplex ultrasound of the abdominal wall vasculature, demonstrating a perforator of the deep inferior epigastric artery pedicle, with both the superficial and deep course able to be mapped relative to the point of perforation of the anterior rectus sheath (asterisk in figures A and B). A: The subcutaneous course of a perforator is demonstrated, superficial to the anterior rectus sheath (asterisk). B: The subfascial and intramuscular course of a perforator is demonstrated (arrow), deep to the anterior rectus sheath (asterisk).

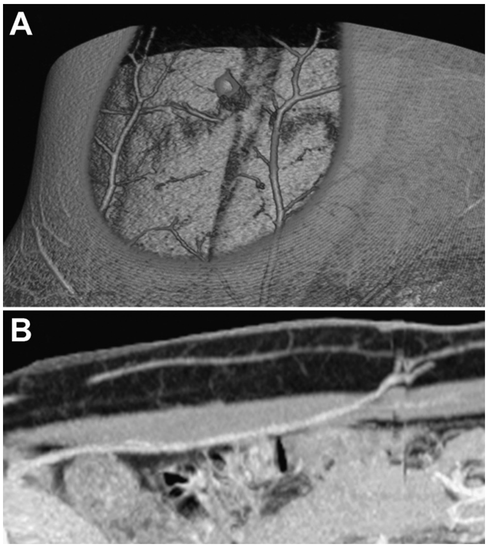

FIGURE 3. CTA of the abdominal wall vasculature. A: An oblique 3-dimensional volume-rendered image demonstrates the subcutaneous course of cutaneous perforators of the deep inferior epigastric artery (DIEA), as well as the superficial venous system. B: A sagittal maximum intensity projection image demonstrates the intramuscular course of a DIEA perforator, from DIEA origin to subcutaneous ramification.

trauma or in assessing the limb for suitability as a free fibular donor. Historically, due to concerns about vascular abnormalities resulting in devascularized limbs following vessel division, imaging was advocated as a routine part of the preoperative workup in these cases.[25–30] However, given the invasive nature of this study, which involves arterial puncture and the concomitant risk of pseudoaneurysm and thrombosis, the need for routine imaging of limbs has been frequently challenged in the literature. Numerous case series exist showing a very low rate of imaging abnormalities in limbs with normal pulses[31–35] and have suggested that routine imaging is not required and should be reserved for cases of severe trauma or abnormal pedal pulse examination. These arguments may be less

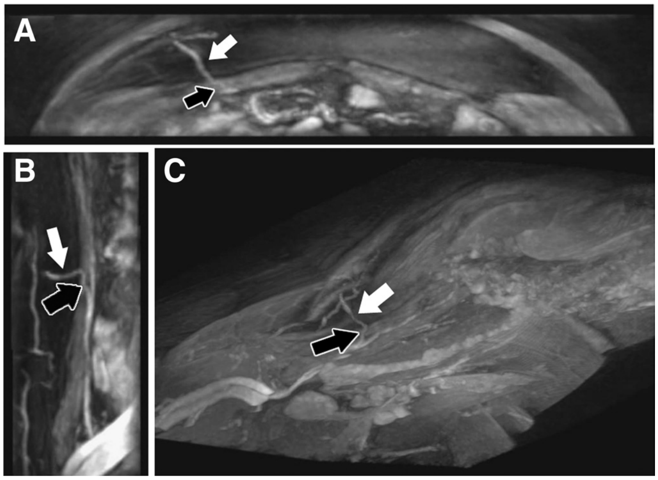

FIGURE 4. Magnetic resonance angiogram of the abdominal wall vasculature, demonstrating the course of a deep inferior epigastric artery, with intramuscular course (black arrow) and subcutaneous course (white arrow) highlighted. Maximum intensity projection 3-dimensional reconstructions highlight the perforator in an axial slice (A), sagittal slice (B), and obliquely (C).

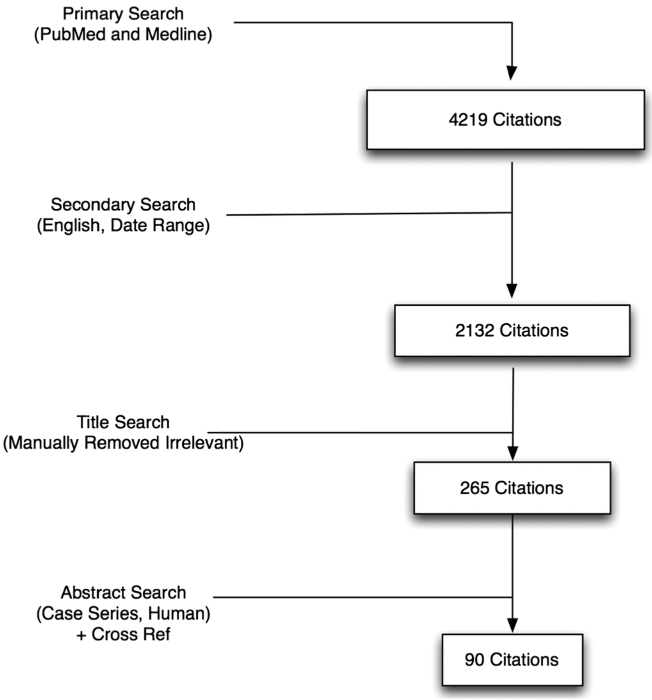

FIGURE 5. Citation attrition diagram showing how the articles in the review were chosen.

compelling in the era of modern imaging techniques such as CTA and magnetic resonance angiography (MRA), which have been proven to be equal to angiography for resolving detail and are noninvasive. The evidence for the use of angiography in preoperative workup in any setting, including perforator assessment is CEBM level 4 (Table 1).

Computed Tomographic Angiography

CTA uses computer-analyzed x-ray images in combination with a bolus of venous contrast medium to produce high-resolution reconstructions of vascular structures. Ongoing advances in CT technology such as increased number of detector rows now allow for faster, more detailed images to be produced, often with a lower radiation dose. Although CTA allows for the production of fine images of the vasculature down to the submillimeter level without the use of intra-arterial contrast, concerns regarding cost and radiation exposure have been raised. CTA has a number of distinct advantages over traditional imaging modalities. It is noninvasive, produces more accurate images than Doppler or color Doppler,[10,23] provides detailed information regarding the intramuscular course of perforating vessels,[36] provides information about other vessels in the scan field, and may give valuable incidental findings.[37]

CT has been used in preoperative assessment of a number of areas of the body. Its initial application was to assess the vessels in settings where catheter angiography had previously been advocated. In particular, the assessment of the recipient vessels in lower limb trauma and head and neck reconstruction, avoiding the potential risks of pseudoaneurysm and embolism associated with classic catheter angiography.[38–41] Over time, this was expanded to include preoperative assessment of the donor limb in planning fibular free flaps[40,42–44] and in recent years to assess the perforators of donor flaps all over the body.

In general, a map of perforator locations as they exit the rectus sheath is produced to a grid system using the umbilicus as the reference point. This information can then be transposed onto the patient's abdomen at the time of surgery. In addition to an extremely accurate spatial map, CTA provides information about the intramuscular course of the vessel and about the superficial inferior epigastric system as well as any abdominal wall defects.

Numerous series have demonstrated the effectiveness of CTA in accurately predicting the location and caliber of the perforating vessels, particularly in planning deep inferior epigastric artery perforator (DIEP) flaps[45–50] and also in ALT flaps.[51–53] However, recently several studies have demonstrated concrete benefits associated with preoperative CTA using case–control models. These benefits include significantly shortened dissection times and operating times,[46,54–59] reduced cost,[54] reduced complications including flap complications and herniae,[46,57,58] and reduced operator stress levels.[59] Interestingly, all these studies were exclusively in the setting of breast reconstruction with abdominal free flaps and no such data exist to support the use of CTA in other free flaps such as ALT or more exotic perforator-based flaps. Nonetheless, this level of evidence elevates the use of CTA in the planning DIEP flaps to CEBM Level 2b (Table 1).

While CTA is criticized for its radiation exposure, some authors present low dose protocols which still offer high resolution images.[60,61] These protocols reduce the dose by reducing the scanning field of the study to include only the area of the abdomen in question. Recent applications of preoperative CTA have included exotic perforator flaps such as superior and inferior gluteal artery perforator flaps,[62,63] superficial inferior epigastric artery flaps,[64] posterior interosseous artery flaps,[65] internal mammary perforator flaps,[66] thoracodorsal perforator flaps,[67] and even mapping of bone perfusion in deep circumflex iliac artery bone flaps.[68]

MRI/MRA

Magnetic resonance imaging uses large magnets which cause the nuclei of hydrogen atoms in the body to align and resonate, emitting a detectable signal which in turn is processed by computers to produce an image in a fashion similar to CT. MRI was developed in the 1970s as an alternative to conventional x-rays for forming medical images. Since that time it has become the imaging modality of choice for many applications, particularly imaging of the soft tissues. Despite this, MRI remains an expensive technology and until recently scanners were not available in all hospitals. In addition, scans are generally slow and many contraindications exist including ferrous medical implants and claustrophobia.

Visualization of the vessels is possible using MRI alone. This technique called flow-related enhancement forms images of the vessels by selectively imaging blood which has moved into the receptor plane at the time of capture. Images produced using this technique were initially lower resolution images, and studies investigating the potential of MRI for mapping the perforators of abdominal free flaps were promising, although of limited resolution.[69] Advances in the field of flow-related enhancement have led to protocol changes and increasingly high resolution images. MRI is now able to resolve detail to a sufficient level to produce acceptable perforator maps.[70] Supplementing the MR scan with nonionizing paramagnetic contrast material such as gadolinium can help to produce even sharper images of arteries.[71] Commonly referred to as MRA, this technique has rapidly found many applications in the preoperative imaging in reconstructive surgery.

MRA has been investigated in the preoperative assessment of legs for free fibular harvest. Its accuracy has been compared with angiography and found to be comparable in this context.[72] Numerous series have demonstrated the utility of this modality for imaging the peroneal vessels[73–75] and recently the technology has been shown to be even more useful in planning free fibular transfers as it is able to resolve detail about the septocutaneous perforators of the peroneal system, thus allowing planning of safe skin paddles.[76,77] In this respect, MRA is superior to angiography in the preoperative planning of free fibular transfers.

MRA has also been used recently in the setting of perforator mapping, especially in the planning of abdominal perforator flaps for breast reconstruction. Small case series have now established the accuracy of MRA with gadolinium contrast in identifying the location and caliber of abdominal perforators,[78] although one series reports a 4% false negative rate (ie, the flap was raised on a perforator not identified by imaging in 4% of cases).[79] One study used a group of controls from the previous year when imaging was not used and demonstrated a lower rate of conversion to transverse rectus abdominis myocutaneous flap in the group which were preoperatively imaged with MRA.[80] One study in 2009 demonstrated that at that time the accuracy of MRA was still inferior to that of CTA.[81]

The level of evidence supporting the use of MRA is CEBM level 3b (Table 1), largely due to a single case control study performed by Neil-Dwyer et al[80] showing improved outcomes in DIEP flap associated with use of MRA preoperatively. MRA has begun to be used in perforator mapping in other anatomic regions including gluteal flaps[79,82] and in lower limb trauma to replace traditional angiography.[83] In addition, imaging of the intraflap venous anatomy of DIEP flaps has been used to identify a cause of postoperative venous congestion.[84]

Image-Guided Stereotactic Navigation

Stereotactic guidance systems have been used for spatial localization in various surgical specialties for some time. They allow the surgeon to accurately define the location of structures and their own instruments relative to preoperatively captured CT or MR scans in real time. This is achieved by placing markers on anatomic landmarks which are then registered by an optical sensor on a computer system. The system can then relate the anatomy of the patient and of surgeons' tools to a precaptured CT scan in real time. Although relatively little published data exist regarding the use of these systems in plastic and reconstructive surgery, much data exist to support their use in other specialties,[85] demonstrating improved operative safety and lower morbidity. This technology has now been used to map out the exact position of perforators in the preoperative assessment of patients undergoing DIEP flap breast reconstruction.[86] In this small series, use of stereotactic navigation software in conjunction with CTA was shown to be feasible and at least as accurate as CTA alone. In addition, this technology has been shown to be feasible in other flaps such as the ALT despite previous concerns regarding the suitability of fiducial marker fixation on nonbony landmarks.[87] One study has examined other methods of computer registration such as registration with surface matching laser; however, it was found that registration of soft tissue was not achievable with this technique and only fiducials were found to be effective.[88] Stereotaxy in the context of reconstructive surgery is in its infancy and the level of evidence assignable to this technology is CEBM level 4 (Table 1).

DISCUSSION

Many imaging modalities are currently used to assess patients preoperatively in microvascular reconstructive surgery. Until recently their use has been ad hoc with some surgeons using preoperative imaging routinely, others in specific cases, and others not at all. In all cases where imaging is used it is intuitively felt to reduce the risk associated with surgery—be the risk of partial and total flap loss due to anomalous perforator anatomy, or risk due to the distal limb when raising a fibular free flap.

As in many aspects of surgery, when assessed objectively the evidence for any of these forms of imaging is limited. This is further complicated by the fact that most studies differ either in modality or in microvascular application making this a very heterogeneous group of studies that it is difficult to draw concrete conclusions from. Regarding imaging of the lower limb, the literature is mixed. A number of studies have suggested that routine imaging of lower limbs before surgery is very low yield except in the context of abnormal pedal pulses or in severe trauma. These studies suggest that this low yield should be balanced against the potential harm of imaging, which traditionally was invasive catheter angiography. While it may be true that clinical examination is very sensitive for assessing the vasculature of the lower limb, arguments against low yield imaging may be less relevant in the era of high resolution noninvasive imaging such as CTA and MRA. At least one survey of surgeons has suggested that many believe it would be "negligent if clinical examination was the only preoperative assessment."[89] In any case, the evidence in question does not go beyond small case series.

Regarding perforator mapping prior to reconstructive microsurgery, there is a large body of evidence to suggest that traditional methods such as the handheld Doppler and color duplex have been superseded. Modern modalities such as CTA and MRA have been shown to be more accurate with less interobserver variation. Unlike other modalities, evidence exists showing improved outcomes when preoperative imaging with CTA and MRA are used. This is particularly so for CTA, in which a number of cohort studies have shown statistically significant reductions in operative time, surgeons stress levels, and improvements in flap outcomes. While this evidence has only been validated for the use of CTA in DIEP flap planning, the proof of concept may allow some extrapolation to other perforator flaps, and there are emerging series showing the use of these techniques in the planning of thigh and gluteal flaps as well as other more exotic perforator flaps.

A recent review article on the subject of monitoring concluded that for flaps with "standard anatomy and superficial vasculature," the handheld Doppler (if anything) should remain the modality of choice.[90] While there were substantial methodological concerns with that study (limited search terms in that review resulted in some key studies demonstrating improved outcomes with CTA being omitted from consideration), preoperative imaging continues to enjoy widespread practice in a number of areas of reconstructive surgery. Even the "humble" handheld Doppler continues to be used in high profile units,[12] and is enjoying a renaissance in the field of free style perforator flaps, no doubt thanks to its ubiquity and portability.

CONCLUSION

Based on current evidence, preoperative imaging is well-supported in the planning of perforator flaps. More so, CTA is advocated as the modality of choice based on current evidence in this role. MRA may well be shown to yet have similar benefits. To conclusively establish the improved outcome suggested by some of these studies, further research is clearly warranted, ideally making use of well-constructed prospective multicenter trials focusing on well-matched homogenous subgroups.

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