Comparison of Various Modalities Utilized for Preoperative Planning in Microsurgical Reconstructive Surgery

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Abstract

Background The benefits of preoperative perforator imaging for microsurgical reconstruction have been well established in the literature.

Methods An extensive literature review was performed to determine the most commonly used modalities, and their applicability, advantages and disadvantages.

Results The review demonstrated varioius findings including decreases in operative time and cost with the use of CT angiography to identification of perforators for inclusion in flap design with hand-held Doppler ultrasound. Modalities like MR angiography offer alternatives for patients with contrast allergies or renal dysfunction while maintaining a high level of clarity and fidelity. Although the use of conventional angiography has decreased due to the availability of less invasive alternatives, it continues to serve a role in the preoperative evaluation of patients for lower extremity reconstruction. Duplex ultrasonography has been of great interest recently as an inexpensive, risk free, and extraordinarily accurate diagnostic tool. Emerging technologies such as indocyanine green fluorescence angiography and dynamic infrared thermography provide real-time information about tissue vascularity and perfusion without requiring radiation exposure.

Conclusion This article presents an in-depth review of the various imaging modalities available to reconstructive surgeons and includes hand held Doppler ultrasound, CT angiography, MR angiography, conventional angiography, duplex ultrasonography, Indocyanine Green Fluorescence Angiography and Dynamic Infrared Thermography.

Keywords
- ultrasound
- imaging
- angiography
- microsurgery

As autologous free tissue reconstruction becomes both more routine and increasingly more complex, attention has turned to the role of imaging in presurgical planning and postoperative care. During the early days of free perforator flap reconstruction in the 1990s, surgeons relied mainly on handheld Doppler ultrasound for perforator identification.[1,2] Over the last few decades, imaging techniques have evolved to include color duplex ultrasonography, multidetector computed tomography (CT) angiography (CTA), conventional angiography, magnetic resonance imaging

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Table 1 A comparison of various available imaging modalities with a focus on their potential advantages and disadvantages

	Accuracy	Reproducibility	Radiation	Safety	Real time	3D relationships	Cost	Vessel flow
Handheld Doppler	++	+	–	+++++	+++	+	+	+
CTA	++++	+++++	++++	+++	+	+++++	+++	++
MRA	++++	+++++	–	++++	+	+++++	++++	++
Conventional angiography	+++++	+++++	+++++	++	+	+++	+++++	+++++
Duplex ultrasonography	+++	+++	–	+++++	+++++	+++	+	++++
ICGF	++	++	–	++++	++++	+	++	+
DIRT	+	++	–	+++++	++++	+	++	+

Abbreviations: 3D, three-dimensional; CTA, computed tomography angiography; DIRT, direct infrared thermography; ICGF, indocyanine green fluorescence; MRA, magnetic resonance angiography.

(MRI), and, more recently, novel technologies such as indocyanine green (ICG) fluorescence and dynamic infrared thermography (DIRT).

Although no single modality has emerged as the uncontested gold standard, the ideal imaging technique should have high fidelity in recognizing location, size, and course of perforator vessels. It should ideally be relatively low risk, involve minimal radiation exposure, and easily reproducible (►**Table 1**). Finally, given the current health care climate, the ideal imaging modality would also need to be cost effective.

A growing body of literature has emerged investigating the impact of preoperative imaging on operative outcomes including operative time, length of stay, donor site morbidity, and surgeon stress level.[3] Although most reconstructive surgeons consider CTA to be the gold standard for preoperative evaluation,[3–5] recent studies suggest that color ultrasonography may be more sensitive and specific for identifying and locating perforators.[6–9]

The purpose of this article is to review the imaging modalities currently available to reconstructive surgeons and discuss the advantages and limitations of each.

Handheld Doppler Ultrasound

Use of handheld Doppler ultrasound for postoperative flap monitoring was first described nearly 40 years ago and has since become the norm at most reconstructive centers.[10] Although unidirectional Doppler does not produce an image and therefore cannot generate a true perforator map, it remains the most commonly used method of preoperative perforator identification, due to, partly, its low cost, small size, accessibility, and relative ease of use.[9] DellaCroce and Sullivan demonstrated that handheld Doppler can be used to ensure inclusion of the superior gluteal artery perforators in superior gluteal artery perforator (SGAP) flap design for breast reconstruction,[11] and Giunta et al similarly demonstrated success in using acoustic Doppler to locate the inferior epigastric artery (IEGA) and superior epigastric artery (SEGA) perforators.[2]

Intraoperatively, handheld Doppler has been used to safely identify the dominant vascular pedicle during intramuscular dissection. Michelow et al described the use of handheld Doppler to identify areas of pulsatile flow and map the location of the arterial supply following exposure of the rectus sheath in TRAM flap reconstruction. The authors reported no flap loss in a series of 66 patients using this technique.[12]

Despite its convenience, use of handheld Doppler is not without significant limitations. Studies have shown a relatively high false positive rate when handheld Doppler is used for perforator identification, and Doppler may not reliably identify perforators that travel transversely through the fascial planes.[2] González et al reported a positive predictive value of 88.6% for handheld Doppler compared with 100% for both CTA and color Doppler ultrasonography. For this reason, reliance on preoperative Doppler may result in suboptimal flap design and threaten the integrity of the pedicle if used alone.[2] In the postoperative period, handheld Doppler cannot always reliably differentiate between local vasculature at the recipient site and the flap's vascular pedicle. Arterial and venous signals originating from vessels within the recipient tissue may therefore give a false impression of anastomotic patency.[13]

Computed Tomography Angiography

Over the last several decades, CTA technology has become increasingly sophisticated and now routinely includes multidetector systems and reformatting software capable of three-dimensional (3D) volumetric analysis. Current scanners are capable of performing submillimeter cuts and can acquire more than 1,000 slices using a single contrast bolus, reducing both total radiation exposure and contrast load.[14] Its favorable risk profile and cost-effectiveness have placed CTA at the forefront of preoperative perforator imaging, and many authors consider it to be the gold standard for evaluating perforator vessels.[3–5] In fact, a recent survey of practicing

Fig. 1 CT angiography showing multiple medial and lateral perforators in the left hemiabdomen in preparation for a DIEP breast reconstruction. CT, computed tomography; DIEP, deep inferior epigastric perforator.

microsurgeons in Belgium, the Netherlands, and Luxembourg showed that 97% preferred CTA for routine postoperative imaging despite the existence of nonradiation requiring alternatives.[15]

The most compelling advantage of CTA is its ability to provide detailed information regarding vessel size, location, course, and anatomic relationships. Perforators as small as 0.3 mm can be reliably identified,[16] considerably smaller than those visualized using other cross-sectional imaging modalities, such as MRA, which is limited to vessels greater than 1 mm in size.[17] CTA has also demonstrated an overall sensitivity and positive predictive value of greater than 95% for mapping perforators. These figures increase to 100% for perforators larger than 1 mm, making CTA an extremely accurate and reliable tool for reconstructive surgeons.[18] Unlike handheld Doppler and duplex ultrasound data, CTA images can be digitally reformatted to provide important information regarding 3D anatomy. This includes arterial branching patterns, the presence of nearby secondary perforators, anatomic relationships with adjacent muscle and fascia, and the presence of potential intraoperative challenges such as scarring or occult hernias (►**Figs. 1** and **2**).[19]

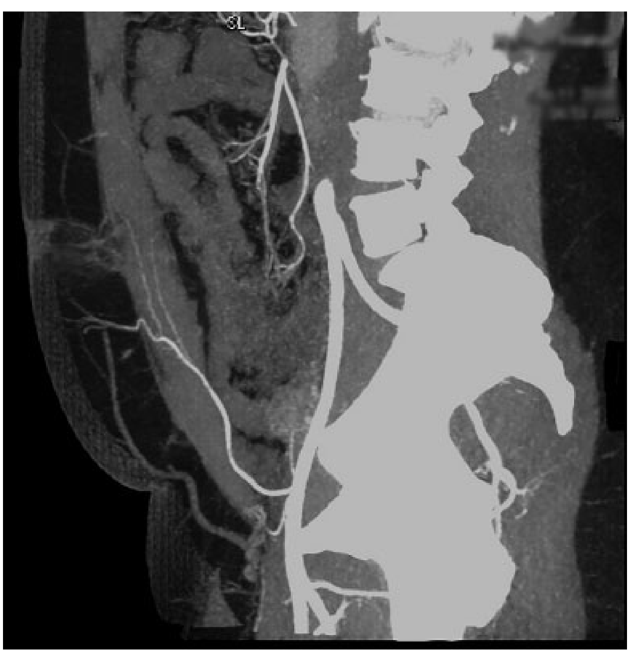

Fig. 2 CT angiography with a sagittal view of the deep inferior epigastric artery along with a dominant perforator. A robust superficial inferior epigastric vein also shown. CT, computed tomography.

Preoperative use of CTA has been shown to decrease total operative time for both unilateral and bilateral deep inferior epigastric perforator (DIEP) flap breast reconstruction when compared with handheld Doppler.[20–22] A recent study by Haddock et al demonstrated that use of preoperative CTA expedited perforator identification and selection, pedicle dissection, and flap harvest.[21] Ultimately, decreased operative times translate into a decrease in operative costs by an average of $3,000 per patient.[20] Preoperative planning with CTA has also been linked to a decrease in postoperative complications including flap loss, partial flap necrosis, hematoma, and surgical site infections, compared with handheld Doppler alone.[20,22]

Despite its multiple attractive advantages, CTA has several significant limitations including the need for intravenous access for contrast administration, use of ionizing radiation, lack of vessel flow dynamics, and inability to demonstrate perforator-specific angiosomes. Although acute kidney injury remains a significant concern, more recent experience suggests that prior studies may have overestimated the incidence and severity of contrast-induced nephropathy, and its true prevalence is likely lower than previously thought.[23,24] Concerns about the risk of contrast allergy may be similarly overexaggerated. Although early hyperosmolar contrast agents were associated with allergy rates as high as 15%, the rate of true allergic reactions to the low osmolality dye used in current studies ranges between 0.2 and 0.7%.[23,25] Despite multiple articles[26–29] falsely citing a single reference,[30] the intravenous contrast dye used in CTA imaging can provoke vasospasm which might impair the detection of smaller perforators, meticulous review of these citations, and the existing literature revealed no evidence to support this claim.

Magnetic Resonance Angiography

Magnetic resonance angiography (MRA) is a noninvasive imaging modality that uses powerful magnetic fields and computer-generated waves to produce high-quality 3D images. Although MR scanners and software continue to evolve, lower strength 1.5-T scanners are generally preferred for reconstructive purposes, as the increase in fat suppression from a lower strength scanner can produce clearer images of vascular structures.[26,31] While MRI has historically been considered most valuable for imaging bone and soft tissue, the addition of intravenous gadolinium contrast can provide additional information regarding blood vessels. Images obtained in the arterial and blood-pool phase allow

Fig. 3 MR angiography with 3D vascular reconstruction demonstrating the arterial supply of the ankle and foot in anticipation for lower extremity reconstruction of a medial plantar wound. 3D, three-dimensional; MR, magnetic resonance.

for selective visualization of arteries and veins without interference from soft tissue enhancement.[29]

Magnetic resonance venography (MRV) protocols can be especially useful in mapping deep and superficial venous outflow in planning complex lower extremity reconstruction.

MRA is an attractive option for routine preoperative imaging because it can provide detailed information about vessel anatomy without the need for ionizing radiation. MRA also offers higher resolution than other imaging modalities, allowing visualization of septocutaneous perforators and vessels as small as 1 mm.[17,32] High-resolution blood pool MRA enables more precise evaluation of vascular anatomy, including a vessel's course, size, and branching pattern, as well as the associated venous arborization pattern.[32] In addition, the presence of architectural distortion, vessel alteration or injury from prior surgery can be easily detected using MRA. This has led some institutions to choose MRI as the reference standard for the preoperative assessment of perforator flap vascular anatomy and soft-tissue morphology.[33] The development of 3D MRI has created additional potential for nuanced evaluation of muscle anatomy in addition to vascular assessment in peroneus brevis flaps prior to surgery (►**Fig. 3**).[33]

Effective use of MRA for preoperative planning has been described for a wide variety of reconstructive procedures, including head and neck reconstruction,[34] DIEP,[35,36] rectus and gluteal muscle flaps for autologous breast reconstruction,[37] and various upper and lower extremity flaps.[17,32,38] MRA does, however, have significant limitations, especially when compared with other cross-sectional imaging modalities. A 2019 review by Rodkin et al showed MRI to be less sensitive in the preoperative detection of perforator vessels when compared with CTA (91 vs. 100%),[36] and an earlier study by Rozen et al showed that CTA was more accurate than MRA for perforator mapping and detection of perforators smaller than 1 mm.[16] In addition, MRI can be time consuming and patients with claustrophobia or comorbidities that limit their ability to lie still for an extended period of time may find it difficult to tolerate. Due to the strength of the magnetic fields involved, all forms of MRI are contraindicated in patients with metal implants, including the metallic access ports within some tissue expanders. Although MRA does not require radiation, it remains one of the most expensive imaging modalities available and its use may be hard to justify in the face of more cost-effective alternatives.[39]

Conventional Angiography

Although conventional angiography remains the gold standard for the evaluation and treatment of coronary and lower extremity arterial disease, its role in the preoperative planning of autologous free tissue transfers has largely been supplanted by less-invasive imaging modalities. Use of angiography was first proposed in the late 1970s to assess the length and size of donor and recipient vessels and to identify potential variations

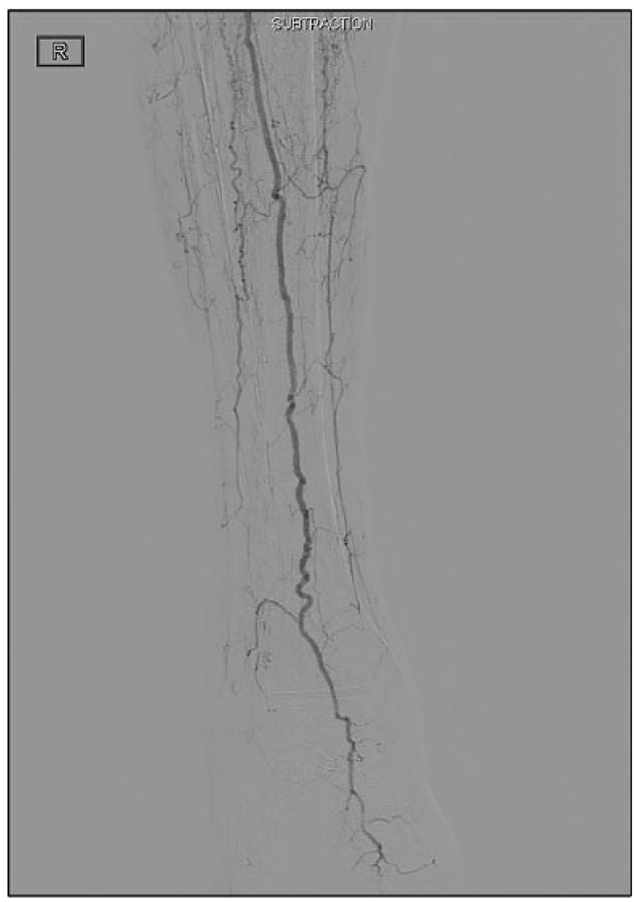

Fig. 4 Digital subtraction angiography demonstrating a single runoff vessel to the lower extremity in anticipation for lower extremity reconstruction of a dorsal foot wound.

in perforator location.[40] Given the number and severity of associated risks, however, use of angiography remained controversial[41] and quickly fell out of favor following the introduction of color flow Doppler (CFD) in the 1980s.[26,42] Recent improvements in cross-sectional imaging modalities such as CTA and MRA have allowed reconstructive surgeons to obtain similar high resolution images without 3 to 5% complication rate associated with traditional angiography.[43] At present, conventional angiography is primarily reserved for the evaluation of lower extremity vascular anatomy, as artifact from metallic orthopaedic hardware may limit the utility of CTA in these cases (►**Fig. 4**).[41,44,45]

Conventional angiography offers high resolution, real-time imaging that enables careful evaluation of both large vessels and smaller perforators. The ability to demonstrate vessel flow dynamics may give invasive angiography a slight advantage over some of the newer imaging techniques, particularly with regard to recipient vessel selection. Conventional angiography can also be used to assess venous anatomy and the adequacy of venous outflow, both of which are vital when planning for complex lower extremity reconstruction. Prior studies have demonstrated effective use of conventional angiography prior to flap harvest. Angiography has been used, for example, as an adjunct in the planning of free fibula flaps when color flow Doppler results were abnormal and additional imaging was needed.[46] In a study of 161 patients undergoing osteocutaneous free fibula transfer, Weng demonstrated that angiography was superior to CFD for detection of vascular abnormalities (55 vs. 14%); however, detection rates between angiography, CTA, and MRA were not statistically different.[44]

Conventional angiography remains a reasonable adjunct to handheld Doppler alone in cases where other imaging modalities are contraindicated or impeded due to the presence of metallic implants. Conventional angiography using carbon dioxide as the contrast medium may be considered as an alternative to CTA in patients with renal failure or contrast allergy, particularly in cases that potentially require large contrast loads.[47] Safe performance and interpretation of CO_2 angiography requires specialist training, however, and its availability may be limited to specific centers.

Duplex Ultrasonography

Recent widespread recognition of ultrasound technology and its advantages over other imaging techniques have contributed to its increased utilization by plastic surgeons. In some centers, duplex ultrasonography has become the imaging modality of choice for preoperative planning in complex reconstructions.[48,49] Duplex ultrasound incorporates both gray-scale and color Doppler imaging, allowing for visualization of anatomical structures and quantification of blood flow velocity and direction.[50,51] Arterial and venous flow can be reliably distinguished using duplex ultrasound, and areas of vessel damage, occlusion, or thrombosis can be identified.[52]

Detailed preoperative perforator mapping using duplex ultrasound has greatly simplified flap design and harvest, especially in flaps known to display considerable variation in vascular anatomy.[53–58] Dorfman and Pu used duplex ultrasound to accurately identify the location, size, and 3D course of anterolateral thigh (ALT) flap perforators, enabling selection of the donor thigh with the largest perforator, most robust blood supply, and the shortest intramuscular course to increase ease of dissection and probability of success.[57] In experienced hands, duplex ultrasonography has been reported to be just as effective as CTA for perforator vascular mapping.[59,60] Use of duplex ultrasonography has also been described for planning vascularized lymph node transfers,[61] monitoring flap perfusion postoperatively,[55,62] and guiding breast-specific reduction patterns based on perfusion.[60,63]

In contrast with other conventional imaging techniques, duplex ultrasonography has the advantage of being noninvasive, portable, and essentially risk free, making a uniquely valuable tool for reconstructive surgeons.[48,54,60] It avoids the use of radiation and nephrotoxic contrast entirely, and can be performed on patients with MR-incompatible metallic implants. The ability to perform ultrasonography at beside significantly shortens image acquisition time, and allows plastic surgeons with excellent knowledge of vascular anatomy to promptly identify developing complications.[64,65]

Universal adoption of duplex ultrasound by reconstructive surgeons has been primarily limited by its steep learning curve. Ultrasound is known to be highly operator dependent and assistance from a certified technologist is often necessary to obtain and interpret ultrasound data.[48,60] Becoming proficient in the use of duplex ultrasound for perforator selection requires training and practice, much of which is not currently provided during surgical residency training. Unlike CTA and MRA, ultrasound does not provide a lasting 3D image that can be easily referenced intraoperatively; however, ultrasound probes can be specially draped for use within the sterile field.

It is important to note that a more in-depth understanding of the various ultrasound modes is necessary to maximize the detection of low flow microvessels. Using prospectively collected data, Kehrer et al were able to formulate an algorithm to optimize vessel mapping. Qualitative vessel data can be obtained with brightness (B) mode, color flow, or B-flow, and power Doppler mode allows for accurate evaluation of small microvessel perforators.[66]

Indocyanine Green Fluorescence Angiography and Dynamic Infrared Thermography

ICG angiography (ICGA) is an emerging technique with multiple potential applications in reconstructive microsurgery.[67] ICG has largely replaced fluorescein dye for use in fluorescent angiography given its nonnephrotoxic properties, strong record of safe clinical use, and low risk of adverse events (1 in 42,000 patients).[67–71] ICG binds well to blood lipoproteins and has a short plasma half-life of 3 to 5 minutes, allowing rapid and repeat imaging to be performed throughout a procedure.[67–70]

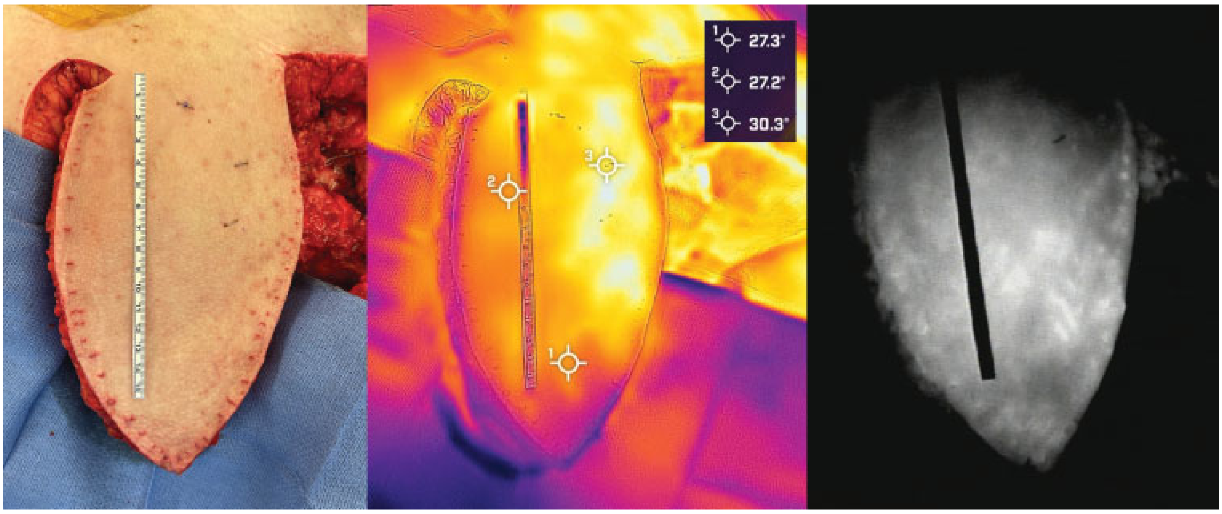

Fig. 5 Comparison of various imaging modalities used as adjuncts intraoperatively to assess distal tip viability of a delayed superior gluteal artery perforator flap including handheld FLIR (middle) and ICGA (right). ICGA, indocyanine green angiography.

In contrast with other imaging modalities, ICGA can provide real-time information about tissue vascularity and perfusion without requiring radiation exposure.[72] Christensen et al and Lee et al described the use of ICGA to determine the optimal timing for second-stage reconstructions and demonstrated that it could be useful in decreasing the probability of flap necrosis.[73,74] Intraoperatively, ICGA has been 90.0% sensitive and 98.6% specific for evaluation of flap perfusion[5,7] and its use has been shown to lower the incidence of unexpected reoperations from perfusion-related complications.[76] Other studies have described the use of ICGA to demonstrate areas of abnormal perfusion and predict potential partial-thickness flap loss, although it has been shown to overestimate flap survival rates in some cases.[77–79]

In a separate study by Ritschl et al, comparison of handheld Doppler and duplex ultrasonography to ICGA demonstrated that this novel modality performed better overall with higher sensitive and positive predictive value in perforator identification.[80]

Overall, recent literature is largely supportive of ICG imaging as an effective adjunct for evaluating tissue perfusion in flap reconstruction (►**Fig. 5**).[69,71,81–84] However, technical use of ICGA remains highly variable across studies, highlighting the need for a standardized protocol that dictates optimal contrast dose, timing of contrast administration, and the need for preoperative allergy testing. Additionally, ICGA is unable to provide continuous perfusion monitoring and its practical applications outside the operating room are currently limited.

DIRT is another emerging noninvasive imaging modality that has shown promise in reconstructive surgery. DIRT provides rapid, continuous, and real-time data regarding skin perfusion indirectly based on measurements of skin temperature. A comparative study by Weum et al demonstrated that DIRT could reliably identify perforators in DIEP flap breast reconstruction, avoiding the radiation and contrast exposure required for CTA.[85] Experimental studies have used DIRT to describe patterns of change in flap skin temperature associated with reperfusion, rewarming, arterial occlusion, and venous congestion.[86,87] Such information may help improve flap design and decrease the risk of flap failure associated with suboptimal geometry and perfusion. Commercially available handheld thermal imaging devices, such as FLIR ONE (Flir Systems, Inc., Wilsonville, OR), are becoming increasingly affordable and can be paired with most smartphones, making DIRT one of the most accessible imaging options (►**Fig. 5**).[88] Furthermore, precooling with a fan or alcohol disinfectant has shown to provide faster results and clearer thermograms.[89]

Pereira and Hallock in a prospective study of 25 patients and 28 perforator flaps evaluated the capability of smartphone thermal imaging cameras (FLIR) for predicting flap viability in lower extremity reconstruction. All flaps predicted to have 100% viability survived, and 40% (two of five flaps) of flaps that were predicted to have marginal loss survived completely. Given its accessibility, versatility, and relatively short-learning curve, the authors supported its use in assisting local perforator flap design, intraoperative management insight, and postoperative monitoring.[90]

Stocco et al performed the first comparative study between smartphone infrared cameras (FLIR) and traditional methods of clinical surveillance (discoloration, capillary filling, and presence of Doppler signal) in the detection of early vascular obstruction in microvascular flaps regarding sensitivity, specificity, positive predictive value, negative predictive value, and time of detection. They concluded that a difference of $\geq$2°C between the flaps to surrounding skin, two times in an hour by infrared thermography for smartphone gave an advantage (93% sensitivity and 96% specificity) in detecting vascular obstruction before clinical signs appear. In some cases, smartphone thermography allowed for the diagnosis of vascular obstruction up to 12 hours earlier than clinical evaluation which can potentially affect flap salvage.[91]

Despite its tremendous potential, no studies to date have shown DIRT technology to be superior to other imaging methods with regards to sensitivity and specificity. At present, therefore, DIRT should be used primarily in conjunction with existing diagnostic modalities.[92]

Discussion

Modern day reconstructive surgeons have the good fortune of being able to enlist an increasingly sophisticated array of imaging options in the preoperative planning, intraoperative decision-making, and postoperative monitoring of microsurgical free tissue transfers. Although no imaging study can ever replace a good working knowledge of anatomy, any of the currently available techniques can provide valuable information regarding flap vascularity or perfusion. As technology continues to evolve toward less-expensive and less-invasive modalities, reconstructive surgeons from a variety of practice environments will likely have increased access to some form of supplemental imaging as part of their routine operative care. The characteristics of the currently available imaging modalities are summarized in (►**Table 2**).

While conventional angiography remains relevant primarily for the evaluation of recipient vessels in lower extremity reconstruction,[93] recent trends have favored less-invasive imaging modalities. Both CTA and MRA can provide detailed 3D images of vascular structures and their surrounding anatomy, and their use has been described in preoperative planning for breast,[3,20,31,64,94,95] head and neck, and extremity reconstructions.[96,97] Although CTA has been shown to accurately detect the location and intramuscular course of perforators less than 1 mm in diameter,[98] a typical CTA of the abdomen requires an average of 6.0 to 9.9 mSv of ionizing radiation which has been shown to be associated with a low but still existent risk of fatal radiation-induced cancer along the order of 1 in 4,270 per 6 mSv.[99] In addition, like conventional angiography, CTA requires the use of iodinated contrast dye which carries a

Table 2 A comparison of various available imaging modalities with a focus on their potential advantages and disadvantages

Imaging modalities	Advantages	Limitations
CTA	• Very detailed resolution and anatomy • Assessment of 3D relationships • Identification of perforations 0.3 mm • Sensitivity and PPV > 95% • ↓ OR times, cost, complications	• Risk of allergy, nephropathy • Ionizing radiation • Lack of vessel flow dynamics
Conventional angiography	• High resolution • Evaluation of vessel flow dynamics • Useful when CTA or MRA unavailable	• Invasive • Risk of vascular injury • Risk of contrast allergy
MRA	• No radiation • High resolution • Visualization of anatomical course • Assessment of musculature • Limit contrast with gadolinium	• Decrease resolution and sensitivity compared to CTA • Time consuming • High cost • Metal implants
Duplex ultrasonography	• Noninvasive • No contrast or ionizing radiation exposure • Well tolerated • Low cost • Portable, bedside applications	• Highly operator dependent • Limited windows, angles, and depth of access; body habitus • Semiquantitative • Relatively low spatial resolution
Handheld Doppler ultrasound	• Ease of use and mobile • Low cost • Use intraoperatively • Postoperative and bedside monitoring	• No visualization • Inability to assess 3D anatomy • Low PPV and high false positive rate
ICGF	• Safer clinical profile compared to fluorescein dye angiography • Can repeat multiple times throughout a procedure • Real-time assessment of tissue vascularity and perfusion • No ionizing radiation exposure	• Unable to provide continuous monitoring of perfusion • Technical use, interpretation, and utilization protocols have yet to be standardized
DIRT	• Rapid, continuous, real-time assessment of perfusion • Safe, noncontact approach • Minimally operator dependent • Can assess large surface areas • No contrast or ionizing radiation exposure • Thermal imaging devices (i.e. FLIR ONE) are becoming increasingly affordable	• "Indirect" technique by assessing temperature • Use is not standardized yet • Not found to have superior sensitivity/specific compared to other modalities

Abbreviations: 3D, three-dimensional; CTA, computed tomography angiography; DIRT, direct infrared thermography; ICGF, indocyanine green fluorescence; MRA, magnetic resonance angiography; OR, operating time; PPV, positive predictive value.

risk of nephrotoxicity and anaphylaxis.[23–25] MRA, while avoiding the need for radiation exposure, is less accurate than CTA for the detection of perforators less than 1 mm in size[16] and is contraindicated in certain patients. In addition, although no study to date has directly investigated the cost effectiveness of various imaging modalities in reconstructive surgery, extrapolation from the vascular literature suggests that MRA is slightly more expensive than CTA.[100,101] For the assessment of venous anatomy, duplex ultrasound, MRV, and the outflow phase of conventional angiography have proven to be the most useful modalities.

Handheld Doppler will likely remain a fixture in reconstructive surgery because of its portability, low cost, ease of use, and versatility. As surgeons become increasingly comfortable performing and interpreting duplex ultrasounds, however, the role of handheld Doppler in preoperative planning and intraoperative decision-making may become more limited. While handheld Doppler has been shown to be less accurate than other modalities in localizing perforators,[2] duplex ultrasound has proved to be highly sensitive and accurate in perforator identification and characterization with the additional advantage of supplying information regarding flow characteristics.[102] A recent prospective study comparing duplex ultrasonography with handheld Doppler and CTA showed that color duplex was more sensitive, specific, and accurate than both other imaging modalities in identification of perforators as small as 0.5 mm, and there was 100% concordance between preoperative ultrasound data and intraoperative findings in 53 consecutive flaps.[9]

While emerging modalities, such as DIRT and ICGA, have substantial promise, they are not yet widely available and their use is currently limited to specific applications. Modern ultrasound equipment, in contrast, continues to evolve toward more portable, accessible, and user friendly interfaces. An increasing number of medical device companies have begun to market handheld duplex ultrasounds such as Lumify (Phillips, Reedsville, PA) or Butterfly IQ+ (Butterfly Network, Inc, Guilford, CT) that can be paired with a smartphone or tablet and offer image clarity comparable to that of conventional ultrasound machines.[59] Although widespread adoption of ultrasound has historically been slow due to lack of familiarity and specialized training, more recent studies have shown that a working knowledge of the newer duplex ultrasound devices can be achieved in a relatively short amount of time.[9,59,103] The consummate masters of human anatomy, plastic, and reconstructive surgeons are uniquely poised to flourish using ultrasound technology.

Conclusion

In the presence of multiple available options, the choice of which imaging modality to incorporate into routine surgical planning and execution rests in the hands of the individual surgeon. While this decision is generally driven by personal experience and institutional preferences, it is important for reconstructive surgeons to continue to reevaluate the risks and benefits of existing modalities and to remain aware of emerging technologies. Ultimately, familiarity with the existing options and flexibility in incorporating new techniques will allow surgeons to continue pushing the boundaries of flap design and harvest in order to make safe and effective microsurgical reconstruction possible for an increasing number of patients.

Conflict of Interest
None declared.

References

1 Blondeel PN, Beyens G, Verhaeghe R, et al. Doppler flowmetry in the planning of perforator flaps. Br J Plast Surg 1998;51(03):202–209

2 Giunta RE, Geisweid A, Feller AM. The value of preoperative Doppler sonography for planning free perforator flaps. Plast Reconstr Surg 2000;105(07):2381–2386

3 Rozen WM, Anavekar NS, Ashton MW, et al. Does the preoperative imaging of perforators with CT angiography improve operative outcomes in breast reconstruction? Microsurgery 2008;28(07):516–523

4 Rozen WM, Ashton MW, Stella DL, et al. Developments in perforator imaging for the anterolateral thigh flap: CT angiography and CT-guided stereotaxy. Microsurgery 2008;28(04):227–232

5 Rozen WM, Ashton MW, Pan WR, et al. Anatomical variations in the harvest of anterolateral thigh flap perforators: a cadaveric and clinical study. Microsurgery 2009;29(01):16–23

6 Debelmas A, Camuzard O, Aguilar P, Qassemyar Q. Reliability of color Doppler ultrasound imaging for the assessment of anterolateral thigh flap perforators: a prospective study of 30 perforators. Plast Reconstr Surg 2018;141(03):762–766

7 Feng S, Min P, Grassetti L, et al. A prospective head-to-head comparison of color Doppler ultrasound and computed tomographic angiography in the preoperative planning of lower extremity perforator flaps. Plast Reconstr Surg 2016;137(01):335–347

8 Mijuskovic B, Tremp M, Heimer MM, et al. Color Doppler ultrasound and computed tomographic angiography for perforator mapping in DIEP flap breast reconstruction revisited: a cohort study. J Plast Reconstr Aesthet Surg 2019;72(10):1632–1639

9 González Martínez J, Torres Pérez A, Gijón Vega M, Nuñez-Villaveiran T. Preoperative vascular planning of free flaps: comparative study of computed tomographic angiography, color Doppler ultrasonography, and hand-held Doppler. Plast Reconstr Surg 2020;146(02):227–237

10 Solomon GA, Yaremchuk MJ, Manson PN. Doppler ultrasound surface monitoring of both arterial and venous flow in clinical free tissue transfers. J Reconstr Microsurg 1986;3(01):39–41

11 DellaCroce FJ, Sullivan SK. Application and refinement of the superior gluteal artery perforator free flap for bilateral simultaneous breast reconstruction. Plast Reconstr Surg 2005;116(01):97–103, discussion 104–105

12 Michelow BJ, Hartrampf CR Jr., Bennett GK. TRAM flap safety optimized with intraoperative Doppler. Plast Reconstr Surg 1990;86(01):143–146

13 Salgado CJ, Moran SL, Mardini S. Flap monitoring and patient management. Plast Reconstr Surg 2009;124(6, suppl):e295–e302

14 Burrill J, Dabbagh Z, Gollub F, Hamady M. Multidetector computed tomographic angiography of the cardiovascular system. Postgrad Med J 2007;83(985):698–704

15 Boer VB, van Wingerden JJ, Wever CF, Beets MR, Verhaegen PD, Hamdi M. Perforator mapping practice for deep inferior

epigastric artery perforator flap reconstructions: a survey of the Benelux Region. J Reconstr Microsurg 2021;37(02):111–118
16 Rozen WM, Ashton MW, Stella DL, Phillips TJ, Taylor GI. Magnetic resonance angiography and computed tomographic angiography for free fibular flap transfer. J Reconstr Microsurg 2008;24(06):457–458
17 Fukaya E, Grossman RF, Saloner D, Leon P, Nozaki M, Mathes SJ. Magnetic resonance angiography for free fibula flap transfer. J Reconstr Microsurg 2007;23(04):205–211
18 Rozen WM, Ashton MW, Stella DL, Phillips TJ, Taylor GI. The accuracy of computed tomographic angiography for mapping the perforators of the DIEA: a cadaveric study. Plast Reconstr Surg 2008;122(02):363–369
19 Hijjawi JB, Blondeel PN. Advancing deep inferior epigastric artery perforator flap breast reconstruction through multidetector row computed tomography: an evolution in preoperative imaging. J Reconstr Microsurg 2010;26(01):11–20
20 Smit JM, Dimopoulou A, Liss AG, et al. Preoperative CT angiography reduces surgery time in perforator flap reconstruction. J Plast Reconstr Aesthet Surg 2009;62(09):1112–1117
21 Haddock NT, Dumestre DO, Teotia SS. Efficiency in DIEP flap breast reconstruction: the real benefit of computed tomographic angiography imaging. Plast Reconstr Surg 2020;146(04):719–723
22 Masia J, Kosutic D, Clavero JA, Larranaga J, Vives L, Pons G. Preoperative computed tomographic angiogram for deep inferior epigastric artery perforator flap breast reconstruction. J Reconstr Microsurg 2010;26(01):21–28
23 Beckett KR, Moriarity AK, Langer JM. Safe use of contrast media: what the radiologist needs to know. Radiographics 2015;35(06):1738–1750
24 van der Molen AJ, Reimer P, Dekkers IA, et al. Post-contrast acute kidney injury - Part 1: Definition, clinical features, incidence, role of contrast medium and risk factors : recommendations for updated ESUR Contrast Medium Safety Committee guidelines. Eur Radiol 2018;28(07):2845–2855
25 Rogers DC, Tadi P. Intravenous contrast. In: StatPearls. Treasure Island, FL: StatPearls Publishing; 2021
26 Smit JM, Klein S, Werker PM. An overview of methods for vascular mapping in the planning of free flaps. J Plast Reconstr Aesthet Surg 2010;63(09):e674–e682
27 Klein S, Van Lienden KP, Van't Veer M, Smit JM, Werker PM. Evaluation of the lower limb vasculature before free fibula flap transfer. A prospective blinded comparison between magnetic resonance angiography and digital subtraction angiography. Microsurgery 2013;33(07):539–544
28 Sheriff HO, Mahmood KA, Hamawandi N, et al. The supraclavicular artery perforator flap: a comparative study of imaging techniques used in preoperative mapping. J Reconstr Microsurg 2018;34(07):499–508
29 Chen FR, Kerluku J, Mintz D, et al. Noncontrast magnetic resonance imaging of perforators for preoperative evaluation of anterolateral thigh flaps. Plast Reconstr Surg Glob Open 2020;8(10):e3174
30 Singh J, Daftary A. Iodinated contrast media and their adverse reactions. J Nucl Med Technol 2008;36(02):69–74, quiz 76–77
31 Vasile JV, Newman T, Rusch DG, et al. Anatomic imaging of gluteal perforator flaps without ionizing radiation: seeing is believing with magnetic resonance angiography. J Reconstr Microsurg 2010;26(01):45–57
32 Akashi M, Nomura T, Sakakibara S, Sakakibara A, Hashikawa K. Preoperative MR angiography for free fibula osteocutaneous flap transfer. Microsurgery 2013;33(06):454–459
33 Kagen AC, Hossain R, Dayan E, et al. Modern perforator flap imaging with high-resolution blood pool MR angiography. Radiographics 2015;35(03):901–915
34 Kelly AM, Cronin P, Hussain HK, Londy FJ, Chepeha DB, Carlos RC. Preoperative MR angiography in free fibula flap transfer for head and neck cancer: clinical application and influence on surgical decision making. AJR Am J Roentgenol 2007;188(01):268–274
35 Rozen WM, Stella DL, Bowden J, Taylor GI, Ashton MW. Advances in the pre-operative planning of deep inferior epigastric artery perforator flaps: magnetic resonance angiography. Microsurgery 2009;29(02):119–123
36 Rodkin B, Hunter-Smith DJ, Rozen WM. A review of visualized preoperative imaging with a focus on surgical procedures of the breast. Gland Surg 2019;8(Suppl 4):S301–S309
37 Newman TM, Vasile J, Levine JL, et al. Perforator flap magnetic resonance angiography for reconstructive breast surgery: a review of 25 deep inferior epigastric and gluteal perforator artery flap patients. J Magn Reson Imaging 2010;31(05):1176–1184
38 Hölzle F, Ristow O, Rau A, et al. Evaluation of the vessels of the lower leg before microsurgical fibular transfer. Part II: magnetic resonance angiography for standard preoperative assessment. Br J Oral Maxillofac Surg 2011;49(04):275–280
39 Mohan AT, Saint-Cyr M. Advances in imaging technologies for planning breast reconstruction. Gland Surg 2016;5(02):242–254
40 May JW Jr., Athanasoulis CA, Donelan MB. Preoperative magnification angiography of donor and recipient sites for clinical free transfer of flaps or digits. Plast Reconstr Surg 1979;64(04):483–490
41 Ahmad N, Kordestani R, Panchal J, Lyles J. The role of donor site angiography before mandibular reconstruction utilizing free flap. J Reconstr Microsurg 2007;23(04):199–204
42 Merritt CR. Doppler color flow imaging. J Clin Ultrasound 1987;15(09):591–597
43 Bluemke DA, Chambers TP. Spiral CT angiography: an alternative to conventional angiography. Radiology 1995;195(02):317–319
44 Weng C. Comparison of color flow Doppler, angiogram, CT angiogram and time resolved MR angiogram in the preoperative evaluation of lower extremity vascularity for fibular free flap reconstruction. Journal of Otolaryngology and Rhinology. 2016;2(01):011
45 Gerlock AJ Jr., Perry PE, Goncharenko V, Franklin JD. Evaluation of the dorsalis pedis free flap donor site by angiography. Radiology 1979;130(02):341–343
46 Smith RB, Thomas RD, Funk GF. Fibula free flaps: the role of angiography in patients with abnormal results on preoperative color flow Doppler studies. Arch Otolaryngol Head Neck Surg 2003;129(07):712–715
47 Cho KJ. Carbon dioxide angiography: scientific principles and practice. Vasc Spec Int 2015;31(03):67–80
48 Cho MJ, Kwon JG, Pak CJ, Suh HP, Hong JP. The role of duplex ultrasound in microsurgical reconstruction: review and technical considerations. J Reconstr Microsurg 2020;36(07):514–521
49 Oni G, Chow W, Ramakrishnan V, Griffiths M. Plastic surgeon-led ultrasound. Plast Reconstr Surg 2018;141(02):300e–309e
50 Cheung ME, Singh V, Firstenberg MS. Duplex ultrasound. In: StatPearls. Treasure Island, FL: StatPearls Publishing; 2020
51 Grant EG, White EM, eds. Duplex Sonography. New York, NY: Springer-Verlag; 1988
52 Mathes DW, Neligan PC. Current techniques in preoperative imaging for abdomen-based perforator flap microsurgical breast reconstruction. J Reconstr Microsurg 2010;26(01):3–10
53 Seidenstucker K, Munder B, Richrath P, et al. A prospective study using color flow duplex ultrasonography for abdominal perforator mapping in microvascular breast reconstruction. Med Sci Monit 2010;16(08):MT65–MT70
54 Tashiro K, Harima M, Kato M, et al. Preoperative color Doppler ultrasound assessment in planning of SCIP flaps. J Plast Reconstr Aesthet Surg 2015;68(07):979–983
55 Figus A, Wade RG, Gorton L, Rubino C, Griffiths MG, Ramakrishnan VV. Venous perforators in DIEAP flaps: an observational anatomical study using duplex ultrasonography. J Plast Reconstr Aesthet Surg 2012;65(08):1051–1059

56 Gao Y, Yuan Y, Li H, et al. Preoperative imaging for thoracic branch of supraclavicular artery flap: a comparative study of contrast-enhanced ultrasound with three-dimensional reconstruction and color duplex ultrasound. Ann Plast Surg 2016;77(02):201–205
57 Dorfman D, Pu LL. The value of color duplex imaging for planning and performing a free anterolateral thigh perforator flap. Ann Plast Surg 2014;72(Suppl 1):S6–S8
58 Lichte J, Teichmann J, Loberg C, et al. Routine preoperative colour Doppler duplex ultrasound scanning in anterolateral thigh flaps. Br J Oral Maxillofac Surg 2016;54(08):909–913
59 Miller JP, Carney MJ, Lim S, Lindsey JT. Ultrasound and plastic surgery: clinical applications of the newest technology. Ann Plast Surg 2018;80(6S, suppl 6):S356–S361
60 Safran T, Gorsky K, Viezel-Mathieu A, Kanevsky J, Gilardino MS. The role of ultrasound technology in plastic surgery. J Plast Reconstr Aesthet Surg 2018;71(03):416–424
61 Patel KM, Chu SY, Huang JJ, Wu CW, Lin CY, Cheng MH. Preplanning vascularized lymph node transfer with duplex ultrasonography: an evaluation of 3 donor sites. Plast Reconstr Surg Glob Open 2014;2(08):e193
62 Arya R, Griffiths L, Figus A, King D, Ramakrishnan V, Griffiths M. Post-operative assessment of perfusion of deep inferior epigastric perforator (DIEP) free flaps via pulsatility index (PI) using a portable colour Doppler sonogram device. J Plast Reconstr Aesthet Surg 2013;66(07):931–936
63 Başaran K, Ucar A, Guven E, Arinci A, Yazar M, Kuvat SV. Ultrasonographically determined pedicled breast reduction in severe gigantomastia. Plast Reconstr Surg 2011;128(04):252e–259e
64 Jacob DD, Kwiecien GJ, Cakmakoglu C, Moreira A. Color duplex ultrasound for localization of vascular compromise in microsurgical breast reconstruction. Plast Reconstr Surg 2020;145(03):666e–667e
65 Swanson E. The expanding role of diagnostic ultrasound in plastic surgery. Plast Reconstr Surg Glob Open 2018;6(09):e1911
66 Kehrer A, Heidekrueger PI, Lonic D, et al. High-resolution ultrasound-guided perforator mapping and characterization by the microsurgeon in lower limb reconstruction. J Reconstr Microsurg 2021;37(01):75–82
67 Alander JT, Kaartinen I, Laakso A, et al. A review of indocyanine green fluorescent imaging in surgery. Int J Biomed Imaging 2012;2012:940585
68 Benya R, Quintana J, Brundage B. Adverse reactions to indocyanine green: a case report and a review of the literature. Cathet Cardiovasc Diagn 1989;17(04):231–233
69 Georgiou AK, Singh P, Hever P, Arize C, Mosahebi A. The use of indocyanine green in plastic surgery. J Plast Reconstr Aesthet Surg 2020;73(09):e8–e9
70 Ott P. Hepatic elimination of indocyanine green with special reference to distribution kinetics and the influence of plasma protein binding. Pharmacol Toxicol 1998;83(Suppl 2):1–48
71 Li K, Zhang Z, Nicoli F, et al. Application of indocyanine green in flap surgery: a systematic review. J Reconstr Microsurg 2018;34(02):77–86
72 Chae MP, Hunter-Smith DJ, Rozen WM. Comparative analysis of fluorescent angiography, computed tomographic angiography and magnetic resonance angiography for planning autologous breast reconstruction. Gland Surg 2015;4(02):164–178
73 Christensen JM, Baumann DP, Myers JN, Buretta K, Sacks JM. Indocyanine green near-infrared laser angiography predicts timing for the division of a forehead flap. Eplasty 2012;12:e41
74 Lee LN, Smith DF, Boahene KD, Byrne PJ. Intraoperative laser-assisted indocyanine green imaging for objective measurement of the vascular delay technique in locoregional head and neck flaps. JAMA Facial Plast Surg 2014;16(05):343–347
75 Lohman RF, Ozturk CN, Ozturk C, Jayaprakash V, Djohan R. An analysis of current techniques used for intraoperative flap evaluation. Ann Plast Surg 2015;75(06):679–685
76 Duggal CS, Madni T, Losken A. An outcome analysis of intraoperative angiography for postmastectomy breast reconstruction. Aesthet Surg J 2014;34(01):61–65
77 Miland Å, Weerd L, Mercer J. Intraoperative use of dynamic infrared thermography and indocyanine green fluorescence video angiography to predict partial skin flap loss. Eur J Plast Surg 2008;30:269–276
78 Hagopian TM, Ghareeb PA, Arslanian BH, Moosavi BL, Carlson GW. Breast necrosis secondary to vasopressor extravasation: management using indocyanine green angiography and omental flap closure. Breast J 2015;21(02):185–188
79 Krishnan KG, Schackert G, Steinmeier R. Near-infrared angiography and prediction of postoperative complications in various types of integumentary flaps. Plast Reconstr Surg 2004;114(05):1361–1362
80 Ritschl LM, Fichter AM, Bomhard AV, et al. Comparison between different perforator imaging modalities for the anterolateral thigh perforator flap transfer: a prospective study. J Reconstr Microsurg 2020;36(09):686–693
81 Burnier P, Niddam J, Bosc R, Hersant B, Meningaud JP. Indocyanine green applications in plastic surgery: a review of the literature. J Plast Reconstr Aesthet Surg 2017;70(06):814–827
82 Pruimboom T, van Kuijk SMJ, Qiu SS, et al. Optimizing indocyanine green fluorescence angiography in reconstructive flap surgery: a systematic review and ex vivo experiments. Surg Innov 2020;27(01):103–119
83 Bigdeli AK, Thomas B, Falkner F, Gazyakan E, Hirche C, Kneser U. The impact of indocyanine-green fluorescence angiography on intraoperative decision-making and postoperative outcome in free flap surgery. J Reconstr Microsurg 2020;36(08):556–566
84 Ludolph I, Horch RE, Arkudas A, Schmitz M. Enhancing safety in reconstructive microsurgery using intraoperative indocyanine green angiography. Front Surg 2019;6(39):39
85 Weum S, Mercer JB, de Weerd L. Evaluation of dynamic infrared thermography as an alternative to CT angiography for perforator mapping in breast reconstruction: a clinical study. BMC Med Imaging 2016;16(01):43–43
86 Tenorio X, Mahajan AL, Wettstein R, Harder Y, Pawlovski M, Pittet B. Early detection of flap failure using a new thermographic device. J Surg Res 2009;151(01):15–21
87 de Weerd L, Mercer JB, Weum S. Dynamic infrared thermography. Clin Plast Surg 2011;38(02):277–292
88 Hardwicke JT, Osmani O, Skillman JM. Detection of perforators using smartphone thermal imaging. Plast Reconstr Surg 2016;137(01):39–41
89 Illg C, Krauss S, Rothenberger J, Kolbenschlag J, Daigeler A, Schäfer RC. Air flow cooling improves anterolateral thigh perforator mapping using the FLIR ONE thermal camera. J Reconstr Microsurg 2022;38(02):144–150
90 Pereira N, Hallock GG. Smartphone thermography for lower extremity local flap perforator mapping. J Reconstr Microsurg 2021;37(01):59–66
91 Stocco C, Papa G, Ramella V, Arnež ZM. Early detection of vascular obstruction in microvascular flaps using a thermographic camera. J Reconstr Microsurg 2019;35(07):e5
92 John HE, Niumsawatt V, Rozen WM, Whitaker IS. Clinical applications of dynamic infrared thermography in plastic surgery: a systematic review. Gland Surg 2016;5(02):122–132
93 Pomposelli F. Arterial imaging in patients with lower extremity ischemia and diabetes mellitus. J Vasc Surg 2010;52(3, suppl):81S–91S
94 Vargas CR, Koolen PG, Ho OA, Tobias AM, Lin SJ, Lee BT. Preoperative CT-angiography in autologous breast reconstruction. Microsurgery 2016;36(08):623–627
95 Zhang X, Mu D, Yang Y, et al. Predicting the feasibility of utilizing SIEA flap for breast reconstruction with preoperative BMI and

computed tomography angiography (CTA) data. Aesthetic Plast Surg 2021;45(01):100–107
96 Zhang Y, Pan X, Yang H, Yang Y, Huang H, Rui Y. Computed tomography angiography for the chimeric anterolateral thigh flap in the reconstruction of the upper extremity. J Reconstr Microsurg 2017;33(03):211–217
97 Haddock N, Garfein ES, Reformat D, Hecht E, Levine J, Saadeh P. Perforator vessel recipient options in the lower extremity: an anatomically based approach to safer limb salvage. J Reconstr Microsurg 2010;26(07):461–469
98 Rozen WM, Ashton MW, Grinsell D, Stella DL, Phillips TJ, Taylor GI. Establishing the case for CT angiography in the preoperative imaging of abdominal wall perforators. Microsurgery 2008;28 (05):306–313
99 Midgley SM, Einsiedel PF, Phillips TJ, Stella DL. Justifying the use of abdominal wall computed tomographic angiography in deep inferior epigastric artery perforator flap planning. Ann Plast Surg 2011;67(05):457–459
100 Froelich MF, Kunz WG, Kim SH, Sommer WH, Clevert DA, Rübenthaler J. Cost-effectiveness of contrast-enhanced ultrasound for the detection of endovascular aneurysm repair-related endoleaks requiring treatment. J Vasc Surg 2021;73(01):232–239.e2
101 Collins R, Cranny G, Burch J, et al. A systematic review of duplex ultrasound, magnetic resonance angiography and computed tomography angiography for the diagnosis and assessment of symptomatic, lower limb peripheral arterial disease. Health Technol Assess 2007;11(20):iii–iv, xi–xiii, 1–184
102 Kehrer A, Lonic D, Heidekrueger P, et al. Feasibility study of preoperative microvessel evaluation and characterization in perforator flaps using various modes of color-coded duplex sonography (CCDS). Microsurgery 2020;40(07):750–759
103 Homsy C, McCarthy ME, Lim S, Lindsey JT Jr., Sands TT, Lindsey JT Sr. Portable color-flow ultrasound facilitates precision flap planning and perforator selection in reconstructive plastic surgery. Ann Plast Surg 2020;84(6S, suppl 5):S424–S430