An overview of current assessment techniques for evaluating cutaneous perfusion in reconstructive surgery

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Abstract

This paper provides a comprehensive analysis of modern techniques used in the assessment of cutaneous flaps in reconstructive surgery. It emphasizes the importance of preoperative planning and intra- and perioperative assessment of flap perfusion to ensure successful outcomes. Despite technological advancements, direct clinical assessment remains the gold standard. We categorized assessment techniques into non-invasive and invasive modalities, discussing their strengths and weaknesses. Non-invasive methods, such as Acoustic Doppler Sonography, Near-Infrared Spectroscopy, Hyperspectral Imaging Thermal Imaging, and remote-Photoplethysmography, offer accessibility and safety but may sacrifice specificity. Invasive techniques, including Contrast-Enhanced Ultrasound, Computed Tomography Angiography, Near-Infrared Fluorescence Angiography with Indocyanine Green, and Implantable Doppler Probe, provide high accuracy but introduce additional risks. We emphasize the need for a tailored decision-making process based on specific clinical scenarios, patient characteristics, procedural requirements, and surgeon expertise. It also discusses potential future advancements in flap assessment, including the integration of artificial intelligence and emerging technologies.

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Introduction

In cutaneous reconstructive surgery, we count on different workhorses. Depending on the extent of the defect, the reconstructive ladder in Plastic surgery is used for evaluation and method selection. This ladder starts with the primary closure, followed by the free skin grafts, local flaps, pedicled flaps and ends with free flaps. [1, 2] A skin graft does not have its vascular supply, whereas a flap is always connected to a vascular system. [3] Flaps can be of different supply patterns and are regularly used for defect reconstruction in larger skin and subcutaneous defects.

Best medical care needs preoperative planning and peri- and postoperative assessment of flap perfusion. A key to successful reconstructive surgery is the necessity for preoperative planning and intra- and postoperative assessment of flap perfusion to limit necrosis or flap loss. [4] Preoperative flap planning has evolved in recent times. In the past, flap planning was based on surgical and anatomical landmarks and flap proportions. However, modern techniques, such as the use of CT-angiography that enables perforator mapping as well as pre-/and intraoperative assessment, have enhanced surgical outcomes in individual cases. [5, 6] Despite progressive medical and technical developments, there is currently no available method that permits a uniform, simple, valid and cost-effective flap perfusion assessment. The gold standard methods mainly rely on the surgeon's clinical assessment [7, 8], which involves observation of skin colour, temperature of the flap, capillary refill, and bleeding pattern [7, 9, 10]. Similarly, surgical re-exploration is a valid way to clinically assess perfusion, especially in the case of local and pedicled flaps. [11]

In an era of rapid technological advancement, as the field of reconstructive surgery continues to evolve, it becomes imperative for the surgeon to navigate through a multitude of technical solutions for assessing flap perfusion without feeling inundated. It is essential to possess a discerning understanding of when and how each method proves effective, is economically viable, and possesses the necessary sensitivity to genuinely inform clinical decisions in flap surgery.

This paper aims to furnish a thorough analysis of modern techniques employed in the assessment of flaps in cutaneous surgery. For this paper, we classify investigative modalities as non-invasive and invasive. Any necessary insertion of contrast medium, probes or needles into the patient is classified and treated here as an "invasive" method.

Surgical anatomy and physiology of the skin

As demonstrated in Figure 1, the skin (cutis) consists of two layers of different thicknesses, the epidermis and the dermis. [12] Underneath are subcutaneous tissue, fascia and muscle. [13] The epidermis comprises the covering epithelial layer, this is also where skin colour is controlled by the density of the resident melanocytes, while the dermis is the carrier of the vascular/nerve supply and collagen fibres. The superficial part of the epidermis is interlocked with the dermis via the stratum papillare so that a tangential displacement of these layers is not possible in a separable way. [12] In this respect, displacements and thus, flap mobilization takes place in the subcutis. While the subcutis can be prominent in terms of thickness in regions such as the cheek, there are areas such as the eyelids or the auricular anterior surface, as well as the lateral columella, where this layer is virtually absent. [12] The vessels of the skin consist of two vascular plexuses parallel to the surface, which serve not only for supply but also for thermoregulation. The superficial Plexus is located at the border between the reticular and papillary dermis. The deeper plexus is located between the cutis and subcutis. Both vascular systems are connected by vertical vessels. [12, 14]Mostly on muscles, larger defined arteries (with their accompanying veins) run parallel to the skin surface and send vertical vessels (in addition to vessels from the subdermal plexus) to the skin. Examples here are the superficial temporal artery [15], the supraclavicular artery [16] and the angular artery [17]. From these defined vessels, axial pattern flaps can be formed, i.e. those flaps that are supplied from a defined subdermal vessel. [14]

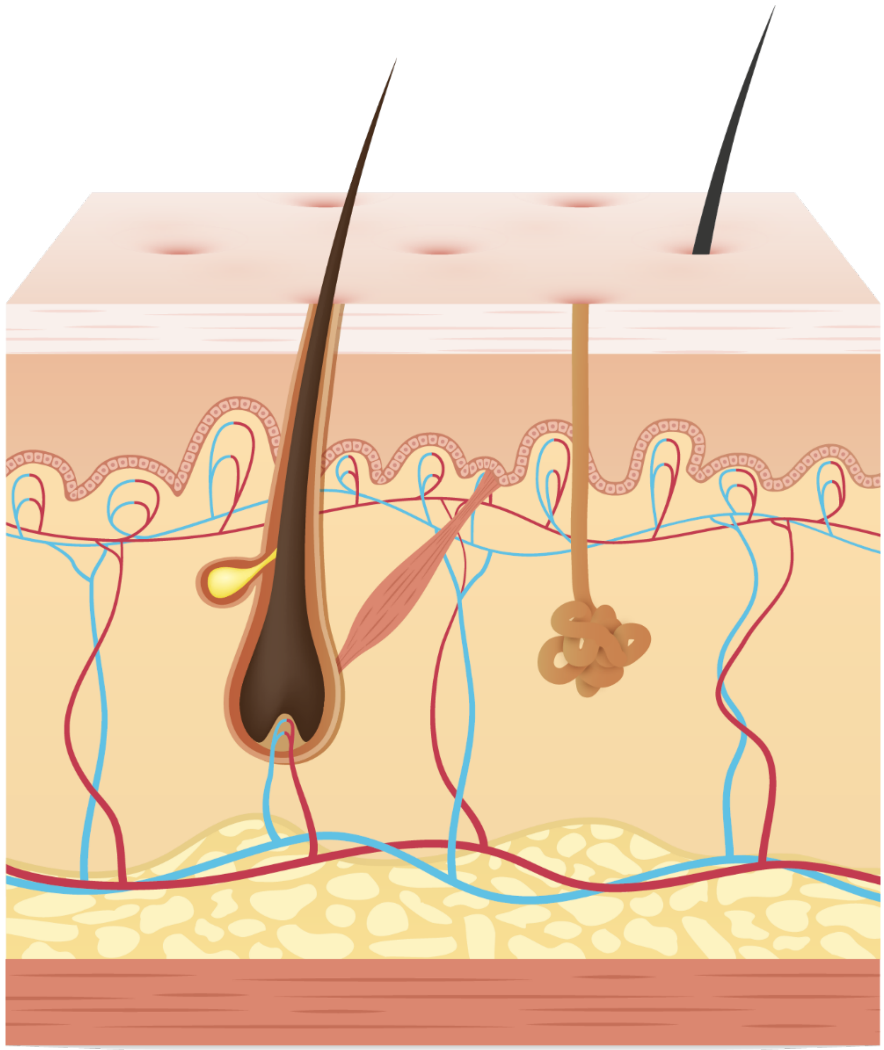

Figure 1 The Skin layers, with vascular structures: A Subpapillary vascular Plexus, B Dermal vascular Plexus, 1 Stratum Papillare, 2 Dermis

Flap design-Anatomical and physiological considerations

There is a ladder of possibilities for how a flap can be supplied by blood. Here we try to differentiate the different flap types due to their supply axis. Pedicled flaps can either be supplied with blood according to a random-pattern principle or if one can define the vascular pedicle or an anatomical axis of supply, as an axial-pattern flap, further as an island flap (again with no definite axis). [3, 13] As was practised in the past, flaps were taken randomly and transferred to the defect after "Autonomization". [18] Autonomization of random-pattern flaps is recommended when the 2:1 length-to-width ratio has to be expanded. In Autonomization, a new blood supply by disconnecting its original blood vessels in axial or random pattern flaps is established by elevating the flap and re-suturing it to the graft bed. This technique not only adapts Oxygen-decrease in the blood but curbs the arterio-venous shunts over vegetative-nervous stimulation. Autonomization of random pattern flaps is recommended when the 2:1 ratio from length to width is extended. [19] After the elevated flap is sutured to his donor bed for at least three weeks, the "Autonomized" flap is then located to the defect area for reconstruction. Further, Autonomization can be used in axial pattern flaps. Therefore Neo-Vascularization of the flap connects it with the wound bed and then, after 3 to 6 weeks, the vascular pedicle can be disconnected. [20, 21]

The use of axial pattern flaps has several advantages: Normally, no delayed surgical procedures are

required, the skin is full-thickness and durable, and excellent cosmetic results can be achieved. In addition, survival rates are significantly higher for axial-pattern flaps (95%) than for flaps that do not have a direct blood supply (53%). [22, 23]

Some examples of axial pattern flaps necessary for the Head and Neck reconstructive surgeon are, the nasolabial flap from the angular vessels [18], the paramedian middle-forehead flap [24] from the supratrochlear vessels and outside the face, for example, the supraclavicular island flap [25, 26], where

the supraclavicular artery is mostly present as an supply-axis.

Aside from axial and random pattern flaps, a third type of vascular supply in flaps is the segmental blood supply which can be seen as a separate flap architecture. So-called perforators, promote an area-related blood supply from the depth to the superficial present as a blood source. The disadvantage of these Perforator-flaps is, that they are sensitive to traction and pressure. [18] Perforator flaps can be pedicled or used as free flap designs with micro-anastomoses and are usually used for the reconstruction of large tissue defects. [27]

Finally -in pedicled flaps- island flaps as a subtype of the axial-pattern flap, are supplied with a non-defined vascular pedicle and the skin "island" cannot be transferred without this supply. [22]

The concept of free tissue transfer through vascular anastomosis was introduced at the turn of the last century but only saw significant development in the 80's. Technical innovations and an enhanced understanding of cutaneous circulation have led to improved outcomes. Successful anastomosis of small blood vessels was achieved in 1960 with the use of an operating microscope. In the same decade, surgeons explored vascular territories serviced by a single arterio-venous system, leading to the description of axial pattern skin flaps. The transfer of such flaps to distant sites with microvascular anastomosis became known as "free flaps." [28] Compared to pedicled flaps, free flaps exhibit distinct anatomical advantages. For one, compared to random pattern flaps, Surgeons are no longer limited by the rule that a flap must not be longer than it is broad (length-to-width-ratio, normally 2:1). Vascularized tissue with a permanent blood supply can now be introduced to devitalized areas, allowing for the repair of complex defects in a single operation.

Perfusion assessment of cutaneous flaps

Despite progressive medical and surgical as well as technical developments, no technique has yet been found that permits a uniform, simple valid and cost-effective intra-/ and postoperative flap perfusion assessment. As a result, direct clinical assessment remains the gold standard. [7, 8]

Clinical control of the grafted area should be based on the assessment of skin colour, temperature, turgor and capillary time by trained medical professionals. [9] Most trained head and neck surgeons assess flap grafts by colour, recapillarisation, scratching (and the quality of the blood) and some by flap surface temperature. [7, 10] Similarly, surgical re-exploration can act as a valid way of clinically assessing local and pedicled flaps. [11]

Non-invasive flap-assessment techniques

Acoustic Doppler sonography (HHD) andColour-coded duplex sonography (DS)

Colour-coded duplex sonography (DS), a vital modality in medical diagnostics, combines the strengths of anatomic visualization and flow assessment through ultrasonography. This technique relies on two primary displays: color-flow Doppler and gray-scale B-mode imaging. Color-flow Doppler provides valuable insight into flow velocity distribution within tissues, highlighting areas of abnormal flow patterns such as turbulence or stenosis. This dynamic representation aids in the identification of vascular pathologies such as arterial occlusions or venous insufficiencies. In contrast, grey-scale B-mode imaging offers detailed anatomical images, allowing for precise localization of structures and abnormalities. This static view complements the dynamic information provided by colour-flow Doppler, enabling a comprehensive assessment of vascular and tissue health. By integrating these two displays, duplex sonography facilitates a thorough evaluation of vascular structures and flow dynamics, enhancing diagnostic accuracy and informing treatment decisions. [29]

HHD is considered the most common and cost-effective technique for finding perforators in breast surgery, for example. (see Figure 2) Although it can determine the relative position of a perforator, it carries the risk of false positive findings (for example other subcutaneous arteries and not perforators) due to its high sensitivity. Furthermore, this modality does not provide information on the exact anatomical course. However, it remains a useful tool for intraoperative evaluation of vessel courses and assessment of perforators. In comparison, DS provides more detailed information on vessel anatomy (see Figure 3), however, it requires in-depth knowledge of the anatomy and is more time-consuming and technically demanding. In comparison with the CTA and MTA mentioned below, the DS is unable to provide three-dimensional information about vascular anatomy. [30]


HUNTLEIGH
dopplex
D900
Aquasonic 100
ULTRASOUND TRANSMISSION GEL
WATER SOLUBLE
HYPOALLERGENIC
PARKER

Figure 2 HHD (acoustic-) Handheld Doppler Sonography ©Fiedler LS.

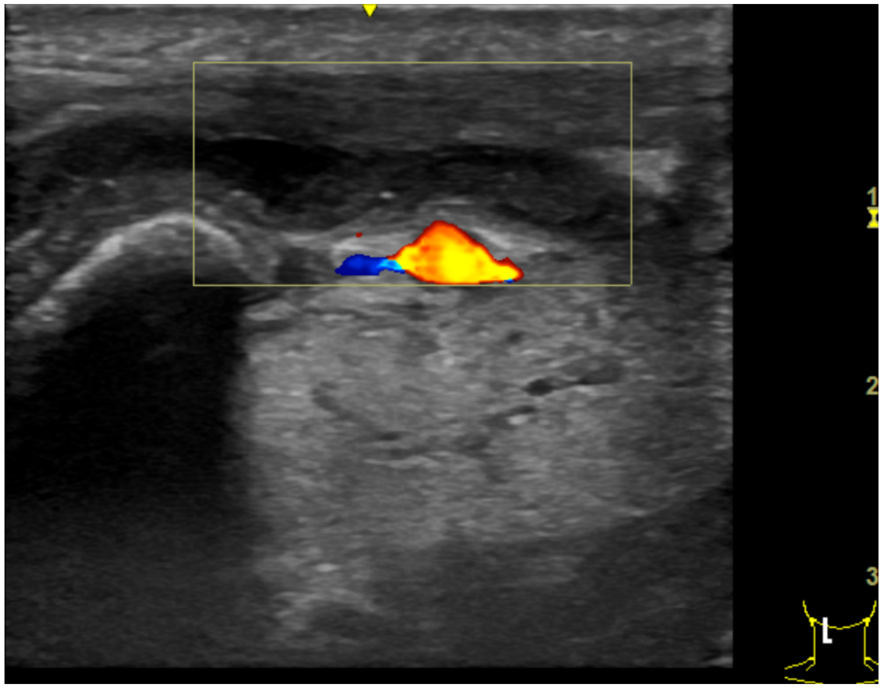

Figure 3 Ultrasound of the facial vein ©Fiedler LS.

Near Infrared Spectroscopy (NIRS)

NIRS is a method that makes use of the near-infrared region of the electromagnetic spectrum. By measuring light scattered off and through a sample, NIRS reflectance spectra can be used to quickly determine a material's properties. [31]

Unlike visible light, which has limited tissue penetration due to shorter wavelengths, near-infrared light (NIR) can penetrate several millimetres into tissues. In skin and muscle, the main absorbing chromophores are the haemoglobin (Hb), myoglobin (Mb), and cytochrome oxidase (cytox), with water and fat also exhibiting absorption peaks at longer wavelengths in the NIR region. Hemoglobin and myoglobin contain iron cores within heme groups, and their absorption of NIR light varies depending on oxygen binding and can be measured by the NIRS instrument. [32]

At the moment, more than 10 commercially available NIRS instruments are on the market. These instruments measure wavelengths ranging from 568 nm to 880 nm. [33] NIRS, therefore is an optical technique that measures changes in oxygen levels in tissues by employing camera-based tissue oximetry. [34] Threshold values for detecting vascular flap compromise varies among studies, with the majority adopting a criterion akin to Keller et al., involving a drop rate in tissue oxygen saturation (StO_2) of 20% or more per hour, persisting for over 30 minutes. Akita et al. introduced a regional oxygen saturation index, with a threshold of 0.75 or lower indicating flap compromise. [33]

In reconstructive flap surgery this method was employed to monitor flap perfusion status, and also to differentiate between venous and arterial vascular compromise within the flaps. It could prove its effectiveness in breast reconstruction with deep inferior epigastric perforator (DIEP) flap, transverse upper gracilis flap, and latissimus dorsi flap with lipofilling. [34] The NIRS technology is highly accurate and has had no false-negative results in several studies. [35] It even can be used in buried flaps. [36] NIRS qualifies even in transcutaneous perfusion assessment, for example in kidney or liver allografts. [37]

Hyperspectral imaging (HSI)

Hyperspectral imaging (HSI) is a technique for capturing more spectral information from an object than a colour camera with typically three colour channels (RGB) can provide. Ideally, HSI can capture a complete spectrum in each pixel. HSI has the potential to provide information about biomarkers as well as distinguish between arterial (oxygenated) and venous blood or different tissue types in real-time. Moreover, it allows for easy, fast, and uncomplicated non-invasive handling.[38, 39] By capturing and analyzing spectral data, HSI enables both quantitative and qualitative evaluation of flaps in real time. Hyperspectral imaging (HSI) facilitates noninvasive and easily recordable assessment of tissue perfusion, with each measurement taking just 5 seconds. Depending on the commercially available system some have to maintain a fixed distance of 50 cm between the camera and the tissue, enabling evaluation of a standardized area of 30 × 30 cm. To ensure high-quality data acquisition, precautions such as minimizing light interference from sources like sunlight and room lighting are advised. The fundamental principle of HSI involves conducting spectroscopic remission measurements within the visible and near-infrared spectral range of 500–995 nm. During imaging, tissues are illuminated, and the resultant altered light reflected from the tissue is analyzed. Haemoglobin, being a principal optical component of tissues, undergoes variations in its oxygenated and reduced forms, particularly between vital and ischemic tissues. Visible light penetrates tissues to a depth of around 0.5 mm, whereas the near-infrared spectral range delves deeper, reaching depths of 3–5 mm, thus influencing microcirculation and blood flow parameters within upper tissue layers.

The software utilized from different systems for analysis extracts four key parameters: superficial skin haemoglobin oxygenation (StO2), superficial haemoglobin concentration (THI), near-infrared spectroscopy (NIR), and tissue water index (TWI). Thresholds for these parameters serve as indicators of local perfusion impairment, where THI values [?]53%, NIR values [?]25%, and TWI values [?]43% suggest compromised perfusion. Specifically, a THI [?]53% at the flap centre may indicate venous congestion. [40] So in conclusion, this technology utilizes the reflection of light at various wavelengths from illuminated tissues to evaluate parameters such as perfusion, oxygen saturation, and haemoglobin content. There is no direct physical contact between the device and the patient, and the findings are presented through colour-coded images displayed on a computer interface. [41] HSI has shown promise in providing valuable information about flap health and perfusion status and has shown superiority in detecting malperfusion in flaps compared with clinical examination within the first 24 hours postoperatively. [41] Furthermore, a systematic review comparing near-infrared spectroscopy (NIRS) and HSI emphasized the reliability, accuracy, and user-friendliness of HSI. [39] Another study focused specifically on HSI's role in perfusion monitoring of free and pedicled flaps[35]. With HSI, signs of deterioration can be detected hours before clinical diagnosis.[39]

Thermal Imaging (TI)

TI and dynamic infrared thermography (DIRT), have now shown promise as an innovative tool in several medical specialties. [42] Thermal imaging technology utilizes electromagnetic radiation in the near-infrared (NIR) range, specifically wavelengths ranging from 780 to 1400 nm. Unlike visible light, which is perceived by the human eye, NIR radiation is invisible and requires technology-based recording, analysis, and interpretation. By employing specialized cameras sensitive to NIR wavelengths, such as infrared cameras, it becomes possible to capture and visualize NIR radiation. [43]

Using the detection of infrared radiation emitted by the body, thermography produces accurate visual representations of surface temperatures, allowing areas of increased or decreased blood flow to be highlighted. [44] (see Figure 4.)

As an advanced, non-invasive and low-cost, mostly smartphone-based [45-49] imaging technique, TI offers valuable insights into graduation of burn depths [45, 46], as well as thermal physiology[42].

TI can provide postoperative monitoring in pedicled flaps that supports clinical assessment with high sensitivity and specificity. A study by Rabbani et al on 84 pedicled and distant flaps showed a 96 per cent accuracy of TI with a sensitivity of 98.7 per cent and specificity of 75 per cent in detecting vascular insults of the flap. [49] DIRT was further described in intraoperative Monitoring in which the skin surface is exposed to a cold challenge and then the pattern of skin rewarming is analyzed. [27]

Since 1968, TI has been known for the first time as an accurate way to assess perforating vessels, so this technique has assisted in finding so-called perforasomes in flap planning. [50-54] In a meta-analysis by Hudson et al, smartphone-based TI was able to detect 378/405 (93.3%) perforating vessels here, while the state-of-the-art method of CT angiography (CTA) detected 402/405 (99.2%). The authors concluded that they had found a cost-effective, safe non-invasive and radiation-free way of assessing free flaps that is independent of all levels of training. [55] TI technology is also already represented in some experiences for monitoring microvascular free flaps [47, 56, 57] For example, Meyer et al were able to confirm a high accuracy of TI in flap assessment in 21 free head and neck reconstructions. [47]

Thus, thrombosis and secondary vessel occlusion can be detected significantly earlier using TI, thus shortening the response time for revision and significantly increasing the probability of survival of the free flap. [57]

Figure 4 Perioperative thermal imaging in a random pattern flap with the FLIR one Pro Camera preoperatively (left), after flap elevation, after reconstruction and 24 hours after surgery (right) showing good perfusion due to the red colour and minor yellow area in the periphery, which shows a low delta between normal and flap temperature ©Fiedler LS.

Remote Photoplethysmography (rPPG)

Remote photoplethysmography (rPPG) is a technology that provides a non-contact measurement of changes in tissue blood volume by analyzing the properties of light reflected from the tissue. [58]

Similar to conventional photoplethysmography (PPG), commonly known as pulse oximetry [59], rPPG technology measures variations in the optical absorption of light and the spectrum of its reflectance, which arise due to the circulation of blood and its corresponding levels of oxygenation. An important feature is that the absorption of light varies depending on the oxygenation state. The diffuse reflectance of different excitation wavelengths can therefore be used to assess the relative differences in absorption between oxygenated (HbO2) and deoxygenated (HbR) haemoglobin. With each heartbeat, pulsatile blood flow generates small oscillations in the reflected light, resulting in a minimal change in skin colour that cannot be seen with the naked human eye but can be easily detected using artificial intelligence. Advanced signal processing and/or deep learning models are then applied to extract colour variations of the skin from video frames using a camera. [60]

Advanced signal processing is then used to extract colour variations on the skin surface from video images taken with (see Figure 5), for example, a normal smartphone camera. [61] Although it was not clear for some time how deep the detection goes in terms of vascular lumen thickness, it has now been proven that deep pulsatile vessels can also be derived using the rPPG technique. [62] This technique can also be used to indirectly differentiate between venous or arterial thrombosis in free flaps during the postoperative phase. [63] In case of compromise of the vascular pedicle, rPPG can also lead to waiting without further compromising the flap, provided the vascular anatomy has been previously visualized by CT angiography. [64]

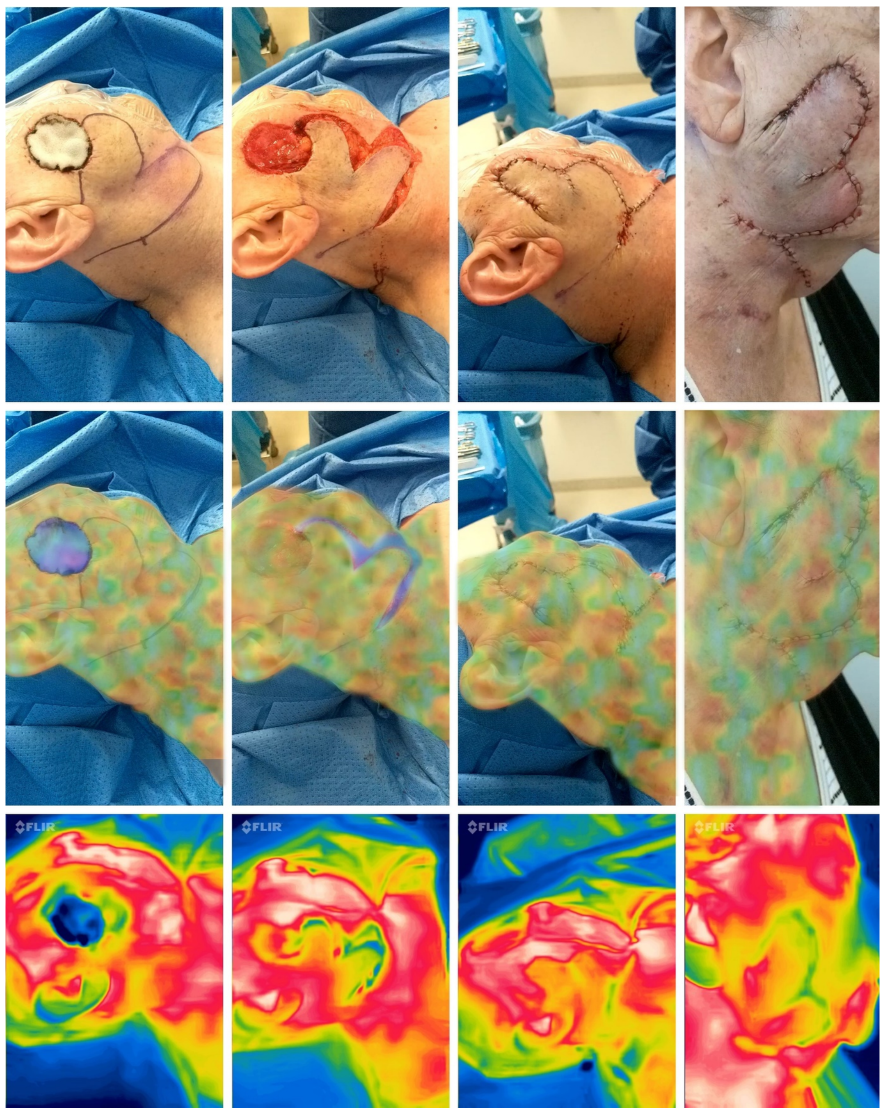

Figure 5 Remote-Photopletysmography showing perioperative imaging in a random pattern flap from preoperatively (left), after flap elevation, after reconstruction and 24 hours after surgery (right) showing good perfusion due to the red colour (Oxygenated blood) and blue areas (deoxygenated)

Invasive flap-assessment techniques

Contrast-enhanced ultrasound (CEUS)

Contrast-enhanced ultrasound (CEUS) employs ultrasound contrast agents (UCAs) to enhance imaging resolution and provide real-time assessment of tissue perfusion. UCAs consist of microbubbles filled with gas, encapsulated by a lipid or protein shell. These microbubbles are small enough to pass through capillaries, enhancing the echogenicity of blood and tissues. During a CEUS procedure, a baseline ultrasound scan is performed to establish tissue morphology. Then, UCAs are injected intravenously, and ultrasound imaging is continued to monitor their distribution within the vasculature and tissue parenchyma. The microbubbles resonate in response to ultrasound waves, producing strong echogenic signals. The timing and intensity of contrast enhancement provide valuable information about tissue vascularity and perfusion dynamics. By assessing the wash-in and wash-out phases of UCAs, clinicians can differentiate between normal and abnormal tissue perfusion patterns. For instance, malignant tumours often exhibit rapid wash-in and wash-out kinetics, whereas benign lesions may demonstrate more prolonged enhancement patterns. [65] As described by Su et al, CEUS is an emerging technology that combines vascular ultrasound with the administration of intravenous contrast agents and thus provides accuracy in, for example, assessing and finding even small-lumen perforating vessels in flap planning. This modality has been shown to have high sensitivity and specificity in finding perforating vessels in anterolateral thigh flaps (ALT) and deep inferior epigastric perforator flaps (DIEP). [54]

Computed Tomography Angiography (CTA)

CT angiography has been an imaging technique since the 1990s that uses ionized radiation in combination with an intravenous contrast agent to produce high-resolution images of the human vascular system. [54] Modern CT scanners can generate high-resolution three-dimensional (3D) datasets with excellent spatial and temporal resolution in a single breath-hold during the first pass of intravenous contrast injection. CTA protocols typically include three phases: non-contrast, arterial phase, and delayed phase, each tailored to specific clinical scenarios. The timing of image acquisition relative to contrast injection is crucial for optimal contrast opacification. Post-processing techniques, such as multiplanar reconstruction (MPR) and maximum intensity projection (MIP), allow for detailed visualization and assessment of vascular anatomy. Additionally, curved planar reformats (CPR) and bone removal techniques enhance visualization, particularly in cases of tortuous anatomy. Advanced methods, such as dual-energy CT (DECT), offer improved differentiation between iodine and bone, further enhancing image quality and diagnostic accuracy. [66] CT-Angiography has several advantages that set it apart from precursor techniques such as Doppler. In comparison, these include higher accuracy, shorter examination times and the visualization of smaller-lumen vessels, including intramuscular vessel courses and the course of perforator vessels. [5, 6]

Near-infrared fluorescence angiography with Indocyangreen (NIRF)

Near-infrared fluorescence angiography (NIRF) provides real-time visualization of vessel structure during surgical procedures. This uses near-infrared fluorescence technology to visualize detailed information about the blood vessels. This is done by injecting a dye -mostly- indocyanine green (ICG) intravenously - binding to albumin in the plasma [67] and capturing images with near-infrared light. NIRF delivers intraoperative visualization of vascular structures, leveraging advanced near-infrared fluorescence technology. By intravenously administering indocyanine green (ICG), NIRF enables real-time imaging of intricate blood vessel networks, as meticulously detailed in the Meta-analysis conducted by Smit et al. This timeframe varies between 12 and 27 seconds. [68]

Depending on the available system, a movable arm allows flexible positioning of light sources and optics over the surgical area. The captured images can be displayed either as still images or as movies on monitors. This technique has proven successful in both preclinical research and clinical applications from vascular surgery over Plastic surgery [67] to breast reconstruction after mastectomy. [69] Perfusion patterns visualized with NIRF imaging are quantified using time-intensity curves, providing various parameters for statistical analysis and visualization. These parameters, including Ingress, Egress, Fluorescence intensity, T_{max}, $T_{1/2}$, and others, allow for standardized quantification of tissue perfusion using NIRF imaging, aiding in clinical decision-making and optimizing surgical outcomes. [67]

It can also be used to assess tissue flap perfusion during surgical planning in the location of perforators to predict tissue flap survival and reduce the risk of necrosis areas. [69-72] As described in the study by Lee et al, near-infrared fluorescence angiography enables real-time visualization of vessel structure intraoperatively. Near-infrared fluorescence angiography can be used in the course of flap planning of perforating vessels and a study by Matsiu et al was able to predict the survival of submental flaps via ICG injections at 0, 0.5, 24, 48, and 72 hours postoperatively via the percentage area of vital perfusing flap areas and predict necrosis areas after 72 hours. [72] In a study by Lohman et al, the above technology application had a high sensitivity of 90 per cent in intraoperative flap planning in terms of blood flow indication. [73] Furthermore, as described by Ludolph et al, this technique can be a viable tool for perfusion monitoring over longer periods and can be used to evaluate free flap-Autonomization. [21]

Implantable Doppler Probe

The Cook-Swartz Doppler Flow Monitoring System (CDSP) is a technique introduced in 1988 by Swartz et al. [74] This method involves securing a 1.0-mm Doppler probe to a cuff of expanded polytetrafluoroethylene (e.g., GORE-TEX), which is then placed around the flap vessel and sutured in place. [75]

The Doppler probe utilizes a 20-MHz ultrasonic frequency and features a 1-mm^2 piezoelectric crystal embedded within a soft silicone sleeve. It connects to a battery-operated or line-powered portable monitor. The probe is secured around the vessel with a small 8x5 mm^2 thin silicone sheet cuff, using sutures or clips. Its proximal end exits as a thin wire through the wound and connects to an intermediate extension cable, sutured to the patient using specially designed retention tabs. This cable plugs into a transportable monitor at the patient's bedside, powered by either battery or mains.[76]

This design ensures precise detection of blood flow velocity and facilitates secure attachment to the blood vessel distal to the anastomosis site, ensuring compatibility with surrounding tissue.[74] During operation, the probe enables simultaneous measurement of velocity and blood flow, establishing a direct correlation between flow and velocity with a relatively low error margin, even under varying flow conditions. [74]

Some authors postulate the addition of implantable systems such as the Cook-Schwartz Doppler probe to the clinical assessment of free tissue transfers. [77] Several cohort studies have demonstrated their usefulness in terms of sensitivity, specificity and false-negative and positive results. This technology can quickly detect compromise, especially in flaps that are not visible and therefore cannot be assessed clinically. [78] However, in a large cohort of 398 breast reconstruction patients, other authors recognized no advantage in the use of Cook-Schwartz Doppler probes; on the contrary, false negative findings of flap compromise were significantly increased. [8]

Comparative Analysis

In the domain of flap surgery, reconstructive surgeons employ a spectrum of both invasive and non-invasive techniques. We provided a comparative analysis of these different techniques where we delve into the nuanced strengths and weaknesses of each approach, with a keen focus on factors such as accuracy, cost-effectiveness, ease of use, and clinical applicability.

Non-invasive techniques offer diverse options. Acoustic Doppler Sonography (HHD) and colour-coded duplex sonography (DS) provide cost-effective solutions, particularly valuable for identifying perforators. HHD excels in breast surgery but may yield false positives, while DS, offering detailed data, can be time-consuming and technically challenging due to its requirement for extensive anatomical knowledge. Near Infrared Spectroscopy (NIRS) effectively measures oxygen level changes and distinguishes between venous and arterial compromise in free flaps, yet lacks dedicated flap assessment systems. Thermal Imaging (TI), a smartphone-based technique, enables early detection of vascular insults but is limited to surface temperature changes, with variable specificity. Photoplethysmography (rPPG) assists in differentiating between venous and arterial thrombosis but may require prior visualization of vascular anatomy.

Invasive techniques introduce different considerations. Contrast-enhanced ultrasound (CEUS) provides accuracy in locating small-lumen perforating vessels but carries risks associated with intravenous contrast agents. Computed Tomography Angiography (CTA) offers high accuracy and shorter examination times but involves ionizing radiation, limiting its use in specific patient populations. NIRF with ICG, an invasive method, enables real-time visualization of vessel structure but entails potential risks associated with intravenous injection. The implantable Doppler probe rapidly detects compromise, especially in non-visible flaps, though controversial findings regarding sensitivity and false-negative results raise concerns about its advantages.

In the overall evaluation, each technique, be it non-invasive or invasive, presents a unique set of advantages and limitations. Non-invasive methods excel in accessibility and safety but may sacrifice specificity. Invasive techniques offer high accuracy but introduce additional risks. The selection between these approaches necessitates a tailored decision-making process, taking into account the specific clinical scenario, patient characteristics, procedural requirements, and the surgeon's expertise. A concise overview of the strengths and weaknesses of each flap-assessment technique, categorized by non-invasive and invasive approaches, is provided in table 1.

TECHNIQUE	Strengths	Weaknesses
NON-INVASIVE	NON-INVASIVE	NON-INVASIVE
Acoustic Doppler Sonography (HHD) Colour-coded Duplex Sonography (DS)	Common and cost-effective method for locating perforators or axial pattern flap pedicles. DS provides a more detailed information on vessel anatomy.	HHD may yield false positives due to high sensitivity. DS demands extensive anatomical knowledge, proving time-consuming and technically challenging. DS is unable to provide three-dimensional information about vascular anatomy.
Near Infrared Spectroscopy (NIRS)	Allows non-invasive measurement of oxygen level changes, demonstrating high accuracy in differentiating between venous and arterial compromise in free flaps.	Currently lacking dedicated flap assessment systems. Higher cost than other systems.
Hyperspectral Imaging (HSI)	Provides effective real-time evaluation of tissue properties and early detection of flap issues.	High-cost No clear superiority over other techniques.
Thermal Imaging (TI)	Non-invasive, low-cost, smartphone-based imaging for early detection of vascular insults. Provides valuable postoperative monitoring in pedicled flaps.	Limited to surface temperature changes. Specificity may vary.
Photoplethysmography (PPG)	Non-contact measurement of tissue blood volume changes, aiding in differentiating between venous and arterial thrombosis in free flaps.	Requires prior visualization of vascular anatomy for effective use during postoperative monitoring.
INVASIVE TECHNIQUES	INVASIVE TECHNIQUES	INVASIVE TECHNIQUES

TECHNIQUE	Strengths	Weaknesses
Contrast-enhanced Ultrasound (CEUS)	Integrates vascular ultrasound with contrast agents, providing accuracy in locating small-lumen perforating vessels.	Invasive nature; may involve risks associated with contrast agents.
Computed Tomography Angiography (CTA)	High accuracy, shorter examination times, and visualization of smaller vessels.	Involves ionizing radiation, limiting use in certain patient populations.
Near-infrared Fluorescence Angiography with ICG (NIRF)	Real-time visualization of vessel structure, aiding in surgical planning and predicting tissue flap survival.	Expensive, Invasive due to intravenous injection; potential risks associated with ICG use.
Implantable Doppler Probe	Rapid detection of compromise, especially in non-visible flaps.	Controversial findings regarding sensitivity and false-negative results. May not offer advantages in all cases.

table 1. Overview of the strengths and weaknesses of each flap-assessment technique

Conclusion The primary goal of perioperative assessment is to ensure optimal flap perfusion, minimizing the risk of necrosis or flap loss. Despite technological advancements, direct clinical assessment remains the gold standard [79], emphasizing the importance of trained medical professionals in evaluating skin colour, temperature, turgor, and capillary refill. Our comparative analysis highlighted the strengths and weaknesses of both non-invasive and invasive techniques. Non-invasive methods, such as Acoustic Doppler Sonography (HHD), Near Infrared Spectroscopy (NIRS), Thermal Imaging (TI), and Photoplethysmography (PPG), excel in accessibility and safety. However, they may sacrifice specificity. Invasive techniques, including Contrast-Enhanced Ultrasound (CEUS), Computed Tomography Angiography (CTA), Near-Infrared Fluorescence Angiography with Indocyanine Green (ICG), and Implantable Doppler Probe, offer high accuracy but introduce additional risks or high cost. The choice of assessment technique should be tailored to the specific clinical scenario, considering factors like patient characteristics, procedural requirements, and the surgeon's expertise. Recommendations for selecting appropriate techniques for different flap types involve weighing the advantages and limitations of each method against the clinical context. Looking ahead, areas for further research and development in flap assessment techniques include refining non-invasive methods for enhanced specificity, dedicated flap assessment systems for NIRS, and exploring novel technologies. The impact of patient preference, clinical setting, and resource availability should be considered when choosing assessment techniques. In essence, navigating the array of flap-assessment tools requires a discerning understanding of their unique attributes. Surgeons must make informed decisions, balancing accuracy, safety, and practicality to ensure successful outcomes in cutaneous reconstructive surgery.

Future perspective

In the realm of reconstructive cutaneous surgery, the future promises an exciting evolution in assessment techniques, with a notable emphasis on the integration of artificial intelligence (AI) and the fusion of current and emerging technologies. As we venture into this era, the convergence of rPPG (remote photoplethysmography) technology, deep learning algorithms, and the principles of ”deep medicine” holds substantial potential for transforming the landscape of flap assessment. Further, these techniques hold great potential to steep the learning curve of young surgeons with bio-feedback techniques to consequently and therefore, improve patient care.

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FL: writing, selection of publications, major revision, minor revision.

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