Review

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Detecting flap compromise: an updated review of techniques to monitor microsurgical flaps post-operatively in breast reconstruction

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Abstract

Breast reconstructive surgery utilizing free tissue transfer has revolutionized the restoration of aesthetic and
functional outcomes for patients. Even for the most routine free flap procedures, substantial hospital resources and
costs are necessary. The effectiveness of free flap surgery, along with any reconstructive procedure, hinges upon
meticulous patient selection, thorough pre-operative planning, well-informed peri-operative decision-making, and
diligent post-operative monitoring and care for the patient. This article presents a review of standard clinical care
monitoring techniques during the post-operative period, as well as the diverse strategies currently employed for
post-operative flap monitoring.

Keywords: Flap monitoring, flap salvage, peri-operative monitoring, post-operative monitoring

INTRODUCTION

Microvascular free flap surgery represents an innovative reconstructive technique that has greatly broadened the possibilities of surgical breast reconstruction[1-3]. Recently, microsurgery has seen a surge in popularity, accompanied by the introduction of new flap types and expanded indications for their use[4]. Nonetheless, the occurrence of flap loss remains a dreaded outcome, with reported failure rates ranging from 2% to 5%[5-7]. The considerable effort, time, and cost invested in microvascular breast reconstruction, spanning from pre-operative planning to post-operative follow-up, intensify the impact of such losses. Pre-operative planning, including possible imaging, may begin several months in advance. Post-operatively, patients are admitted to the intensive care unit (ICU) for hourly flap checks during the first 48 hours, when the flap is most vulnerable[8]. However, evidence has emerged suggesting that patients can be safely managed in step-down units instead of ICUs, allowing for accelerated discharges without an increased risk of flap loss[9]. Nevertheless, the costs associated with autologous breast reconstruction remain high. According to the Healthcare Cost and Utilization Project National Inpatient Sample dataset, the average cost of a deep inferior epigastric artery perforator (DIEP) flap for autologous breast reconstruction amounts to $22,677[10]. Flap failure amplifies this already high cost by 50% to 77%, primarily due to extended hospital stays and the need for secondary operations, thereby further compromising aesthetic and/or functional outcomes for patients[11,12].

Free flaps fail when tissue perfusion is compromised and unable to meet the metabolic demands of the tissue. This occurs from inadequate inflow, inadequate outflow, or intrinsic issues. Among these causes, venous insufficiency is the most frequently encountered, as veins are delicate structures prone to compression or damage from trauma or pressure[13-15]. Certain intraoperative decisions can increase the post-operative risk to the vasculature, such as the presence of perforators with long or tortuous courses. Additionally, elevated tissue pressure, resulting from factors like edema, hematoma, or external compression (e.g., positioning), can surpass perfusion pressure. Certain patient factors (e.g., age, disease, body weight, smoking, pharmacological history), as well as the specific flap type, can further contribute to the risk of experiencing any of these causes[16].

The initial 48-hour period following surgery poses the highest risk for flap failure, emphasizing the importance of employing sensitive strategies for early detection. Timely identification of flap failure can be instrumental in salvaging compromised flaps by prompting an urgent return to the operating room for diagnostic assessment and salvage attempts[8,17-21]. Flaps can be successfully salvaged in 28% to 90% of cases, but this range is highly dependent on the time of detection and take-back[22-25]. As the field of breast reconstruction continues to expand with various options, the challenge of early detection has necessitated the concurrent evolution of advanced flap monitoring techniques. For example, the introduction of nipple-sparing mastectomy, which may involve immediate reconstruction using a buried free flap without a skin paddle, requires the development of reliable monitoring methods independent of cutaneous visualization. In addition to thorough clinical examinations conducted by experienced professionals, several adjunctive post-operative monitoring technologies have been developed to complement physical examinations and contribute to reducing failure rates. This narrative review summarizes the techniques employed to facilitate early detection of threatened flaps in breast reconstruction, encompassing post-operative protocols, clinical examinations, and supplemental technologies. We also highlight novel advancements and future directions in plastic and reconstructive surgery.

POST-OPERATIVE FLAP MONITORING

Most institutions follow specific protocols to ensure standardized care during the vulnerable post-operative period (48 h), typically in the ICU with trained staff and immediate access to the operating room if

indicated. However, protocols vary significantly between institutions and flap types, and there remains no national consensus on the frequency or duration of monitoring. Recent discussions have emerged regarding the necessity of ICU monitoring for free flaps and the utility of monitoring beyond the initial 48 h[26,27]. A meta-analysis of head and neck microvascular reconstruction indicated that immediate post-operative ICU care did not lead to a decrease in flap failure or complication rates[28]. Frequent monitoring with hourly flap checks in the first 24 h is ideal, and this frequency can be decreased to every 4 h for the subsequent 2-3 days[29]. Shorter intervals, such as 30-minute intervals for the first 24 h, are considered optimal but can be time-consuming for surgeons, residents, or nursing staff. Additionally, microsurgical flaps carry the potential for infection and vascular trauma, which, when combined with manual examination and dressing procedures, may result in the development of hematoma and seroma[30]. Nevertheless, the primary objective of any post-operative monitoring protocol should be to optimize the patient's recovery and expedite their return to pre-operative status, thereby reducing hospital length of stay, the risk of infection or deep venous thrombosis, and costs of care[27]. Emerging research suggests that the implementation of an enhanced recovery after surgery (ERAS) program, which incorporates a transdisciplinary comprehensive approach to peri-operative care, may effectively reduce post-operative complications, shorten the length of stay, and minimize the need for morphine equivalent dosing[31]. High-volume institutions and greater provider experience have been associated with lower rates of flap failure, indicating the beneficial role of protocols[32,33]. Typically, patients are placed on strict bed rest and "nothing by mouth" for the first 24 h to prevent mechanical complications and allow for prompt re-exploration, if necessary. Volatile hemodynamic disturbances are avoided by using appropriate anesthetic/pharmacologic agents[20,34,35]. The use of anticoagulation remains controversial due to the delicate balance between undesirable bleeding and the risk of thrombosis[36]. However, prophylactic administration of heparin can be employed for deep-vein thrombosis prevention. Aspirin can be given for up to 30 days to inhibit platelet aggregation[37]. Low-molecular-weight heparin and aspirin, either alone or in combination, have shown similar efficacy in reducing macrovascular graft occlusion after surgery[36]. Lastly, patient education about the planned monitoring can help to manage their expectations, improve compliance, and enhance both flap outcomes as well as the overall patient experience[38].

Bedside clinical evaluation

The clinical exam remains the cornerstone of flap monitoring after breast reconstruction, offering high sensitivity and effectiveness in detecting failing flaps without incurring the expenses associated with advanced monitoring technologies or specialized personnel. The clinical exam comprises four essential components: color, capillary refill, tension/turgor/swelling, and temperature [Table 1][39]. Unlike software-based techniques, the clinical exam has the capability to discern between adequate inflow (arterial) and outflow (venous) problems[39]. While not all patients will have a drain post-operatively, checking the drain's functionality, output color, and amount remains an important aspect of the clinical exam.

The effectiveness of the clinical exam relies heavily on the experience of the provider, who may assign varying importance to specific exam findings. Furthermore, patient-specific factors, such as skin tone and flap location, can influence findings; color changes, for instance, may be less pronounced in patients of different races and/or ethnicities[40,41]. The clinical exam has limitations in cases where flaps lack a cutaneous component (e.g., musculocutaneous flaps and other buried flaps). In such instances, surgeons may opt to expose a small portion of the flap at the skin surface temporarily to facilitate monitoring. Advanced monitoring technologies are particularly valuable when the clinical exam yields ambiguous or inconclusive results[42].

Table 1. Clinical examination findings

	Characteristics	Arterial	Venous
Visual	Color	Pale	Cyanotic, dusky
	Capillary Refill	Delayed (> 3 secs)	Shortened (< 2 secs)
	Pinprick	Decreased	Dark venous outflow
Tactile	Temperature	Cold	Warmth
	Tension/Swelling	Mild swelling (late finding)	Increased turgor

Adjunctive techniques

Medical devices manufacture is an evolving field and an area of ongoing research. The objective of developing flap monitoring devices is to create compact, portable techniques that can provide consistent, real-time quantitative data on flap viability and perfusion[43-47]. The data obtained should be objective and not provider-dependent[48,49]. This data can assist surgeons in assessing flow patterns, quality, severity, and determining the need for reoperation[50].

Typically, techniques for flap monitoring are categorized as either non-invasive [Tables 1 and 2] or invasive [Table 3]. Multiple devices can be used in combination as adjuncts to the clinical exam. Generally, non-invasive techniques are more user-friendly, readily available, and cost-effective. Quantitative results that can be tracked over time enhance the sensitivity of detecting flap failure. Monitoring devices may enable flap monitoring without direct contact with providers, which was advantageous during the COVID-19 pandemic[51]. However, it is important to note that absolute values may have limitations and lack consistency between patients. Further, the use of monitoring machines may entail costs and require specialized expertise[48].

Non-invasive techniques

Photoelectric assessment with Doppler monitoring

Doppler ultrasonography is widely recognized as one of the most effective and commonly used non-invasive methods for flap monitoring, with acoustic Doppler devices being the most predominant choice. Acoustic Dopplers operate by emitting sound waves of a specific frequency, phase, and amplitude into the tissue. These sound waves reflect off moving matter, primarily the red blood cells within the intravascular arterial and venous system in flaps. The movement of these cells leads to a slight shift in the frequency of the reflected sound waves, known as the Doppler effect, hence the term "Doppler". The machine converts and transmits these reflections into an audible noise, which exhibits a pulsatile pattern in arterial flow and a quieter, more consistent pattern in venous flow[52-54]. Marking arterial and venous acoustic signals at the conclusion of the procedure with a single stitch can facilitate post-operative monitoring[55]. Acoustic Doppler sonography is a user-friendly technique that requires minimal training, and the devices are widely available, cost-effective, and highly portable[54]. However, it is important to note that the absence of a signal does not always indicate inadequate blood supply for flap viability, and the signal from key perforators may be difficult to distinguish from background noise caused by other vessels[53].

Laser flowmetry is another Doppler-based method employed for flap monitoring, although it differs from acoustic Doppler by measuring in *light* waves instead of *sound* waves[56]. Laser flowmetry probes are secured to the skin surface overlying the target vessel using dressings or sutures[57,58]. The data output provides real-time measurements of skin surface blood velocity and blood flow, which are accurate up to a depth of 8 mm[13]. However, these values only serve as relative indicators of blood flow, and while trends within the same patient are reliable, the data can be significantly influenced by various patient- and device-related factors[57,59]. As a result, there is no clear "cut-off" value suggestive of vascular compromise. Instead,

Table 2. Non-invasive techniques for flap monitoring including main benefits and limitations

Non-invasive technique	Benefits	Limitations
Physical examination	● Combines several signs (visual, tactile, drain output) to determine the risk of flap failure ● Opportunity for patient interaction to counsel, manage anxiety and concern, provide answers to questions, and participate in shared decision making post-operatively (e.g., ensuring bed rest and "nothing by mouth")	● Subjective to provider's gestalt and experience ● Not quantitative ● Limited in flaps without cutaneous portion ● Lack of continuous monitoring
Acoustic doppler ultrasonography	● Minimal training required ● Highly portable, bedside utilization ● Cost effective ● Intra- and post-operative use ● Simple to pair with concurrent physical examination	● Accuracy can be impacted by noise from vessels near the target vessel ● Blood flow detected is not always sufficient to sustain flap ● Unsuitable for buried flaps
Laser doppler flowmetry	● Intra- and post-operative flap use ● Relatively easy to interpret and can be monitored by many members of the care team ● Blood flow velocity readings are continuously reported, giving a quantitative picture of blood flow ● Accurate flow and velocity measurements in vessels up to 8 mm deep	● Blood flow measurements are not absolute but relative, depending on specific device and patient parameters, making a definitive threshold for vascular compromise elusive ● Many of the pieces of the laser flowmeter apparatus are fragile and can be easily broken by patients and providers alike False reports of inadequate flow can be reported when a blood clot or other obstruction blocks the laser's path
Color duplex ultrasound	● Improved sensitivity for detection of vascular compromise compared to other Doppler methods ● Can detect and discern discrete vascular pathologies	● Large and unwieldy ● Requires expert operation by a technician as well as the presence of an attending microsurgeon or resident to orient the device ● Expensive to acquire and maintain ● Not as useful in the intraoperative setting
Surface temperature monitoring with/without infrared thermal device	● Cost effective ● Bedside ● Real-time ● Not provider dependent ● Can be non-contact ● Quantitative ● Trends can be monitored overtime	● Limited value in isolation without combined clinical judgment (spurious results possible, e.g., if not in contact) ● Cannot be used in flaps without cutaneous portion
Tissue oximetry	● Bedside ● Real-time ● Not provider dependent ● Quantitative ● Trends can be monitored overtime ● Highly portable	● Readings influenced by ambient light ● Readings influenced by patient movement ● Readings can vary by device type ● Different skin colors have been reported to produce different results ● Does not directly assess vascular patency (measures end tissue oxygenation) ● Cost

significant drops or variations in measurements are used to indicate changes in flap perfusion, and this can be easily discerned by healthcare personnel and family members. It should be noted that laser Dopplers employ delicate fiber optic cables that are easily damaged. Finally, false reports of inadequate flow are not uncommon, even when the tissue is well-perfused, such as in cases when a blood clot or other obstruction disrupts the laser's path[50].

Color duplex ultrasound is a less commonly employed Doppler-based method for non-invasive flap monitoring, utilizing a device that emits and detects the entire visual spectrum of light[60]. The device detects the Doppler effect, which is the change in frequency between the emitted and reflected visible light waves. These light waves are transduced to create a grayscale ultrasound image that is augmented with color to indicate the direction and position of blood flow. Color duplex ultrasound has proven successful in monitoring various flaps with different vessel sizes, including fasciocutaneous perforators for DIEP flaps[61]. A variant device known as "power Doppler imaging" uses higher frequency waves to detect vessels with smaller diameters, reaching as low as 0.2 mm[62]. Color Doppler ultrasound is highly sensitive in detecting compromised vessels, enabling the assessment of vessel caliber, patency, flow characteristics, anomalies, and

Table 3. Invasive techniques for flap monitoring, including main benefits and limitations

Invasive technique	Benefits	Limitations
Implantable doppler & venous coupler	● Cost effective ● Usable on all types of flaps ● Ease in signal reading	● May cause vessel damage ● Complex operative technique ● High false positive rates
Transcutaneous oxygen tension monitoring	● Very sensitive to declines in tissue oxygenation ● Easy to monitor ● Can be used for monitoring of buried flaps ● Provides a direct measurement of oxygen availability at the cellular level	● Invasive, requires tunneling with some extra dermal components ● May be unreliable in large cutaneous flaps or flaps with large within-flap temperature gradients
Biochemical markers	● Cost effective ● Reflect the flap's local environment ● Patterns of known metabolites exist to direct thresholds and clinical decisions	● Limited efficacy among diabetic patients ● Not applicable for buried flaps
Microdialysis	● Can be used when clinical examination is not possible ● Detects flap failure hours before it becomes clinically evident ● Gives a quantitative metric	● Causes local tissue trauma ● Cost ● High false-positive rates ● May require an equilibrium period ● Securing the catheter can be difficult
Fluorescence imaging	● Broadly used with clinical applications beyond plastic surgery ● Can leverage different fluorophores ● Handheld devices and probes have been developed ● Ease of use	● Additional staffing requirements are not as high as other techniques ● Continuous monitoring is difficult ● Repeat injections of dyes may be required ● Limited circulation of fluorophores
Technetium-99m sestamibi scintigraphy	● Can monitor muscle flap viability reliably ● Reveals distal ischemia or hypoperfused area in muscle tissue ● Short half-life of ~6 h	● Limited to a majority of case reports and series with the need for more robust studies ● May need to be combined with other techniques, such as Doppler, to visualize the blood vessel integrity
Perfusion-weighted MRI	● Is relatively non-invasive, and risks to the patient are limited to those imposed by the administration of contrast ● Provides a picture of entire-flap perfusion	● Resource intensive ● Requires support staff at each step ● Requires serial studies if flap is to be monitored over time

pathologies[54]. However, its specificity in identifying vascular compromise, like other Doppler devices, is limited. Color duplex ultrasound machines are more expensive, less portable, and require trained personnel for operation. Typically, the presence of a microsurgeon is necessary to aid in the anatomical orientation of the transmitter, while a radiology technician is required for consistent image acquisition and interpretation.

Surface temperature monitoring
In addition to tactile assessment in the clinical exam, flap temperature can be measured and monitored using temperature probes placed on the skin surface. The arterial blood supplying the flap carries heat, which is released into the surrounding extravascular tissue through convection[63]. Congested flaps exhibit distinct temperature drop patterns compared to ischemic flaps. A temperature drop of 3 °C (37 °F) at the center of a skin paddle indicates arterial thrombosis, while a uniform temperature drop of 1-2 °C (33.8-35.6 °F) across the skin surface of a flap suggests venous compromise[64]. Typically, surface temperature monitoring can detect flap compromise starting from the eighth hour post-operation[65]. Measurement of flap temperature can be easily performed using inexpensive strips (~1$ per strip) placed on the surface of free flaps, and the values can be compared to the temperature of adjacent non-operated skin[66].

Recently, infrared thermography has emerged as a novel method of post-operative flap monitoring in breast reconstruction[67,68]. This thermal imaging technology converts the detected temperature values through infrared radiation into pixel values, resulting in a visual display of cutaneous blood flow. Infrared thermography has demonstrated a sensitivity of 96% and a specificity of 75%, indicating its potential as a valuable adjunct to clinical assessment[67].

Surface temperature monitoring has its limitations when applied to buried and intraoral flaps[69], and it can be influenced by various external factors, including ambient room temperature and air flow. Research suggests that in patients who have undergone DIEP breast reconstruction, surface temperature monitoring using a dual-channel digital thermometer (Raytek, Norway) lacks sensitivity and is inferior to clinical examination conducted by trained nurses[70]. In the case of large perforator flaps such as DIEPs, the temperature difference between the flap surface and adjacent non-flap surface may be minimal, reducing the utility of surface temperature monitoring. However, it may still have value in monitoring perfusion in scenarios like digit replantation and small free flap reconstruction[71].

Mobile smartphone monitoring technology
Given the widespread use of smartphones, leveraging this technology to enhance communication and enable remote post-operative monitoring through adjunct devices presents a rapid, cost-effective, and non-invasive option for early detection of free flap failure.

Innovative text messaging systems that alert surgical teams of post-operative monitoring tissue oximetry readings below a certain threshold show promise in identifying potential flap loss and facilitating prompt notification[72]. With smartphones equipped with advanced digital photography capabilities, earlier discharge and continued remote flap monitoring at home with improved communication between patients and healthcare staff may soon become possible. Studies suggest that the use of remote digital photography may even lead to reduced response time to re-exploration and improved flap salvage rates[39,73]. The usefulness of digital photography by patients becomes even more apparent when uploaded through dedicated post-operative monitoring platforms, enabling easy comparison with previous images[74]. By employing free applications on smartphones, continuous real-time streaming of free flap tissue to surgeons for decision-making can be achieved[75]. Kiranantawat *et al.* developed a smartphone application that identifies color changes indicative of compromised flaps for monitoring purposes[76]. Furthermore, the integration of machine learning algorithms holds the potential to reveal previously undetectable findings to the human eye[77].

Digital thermographic cameras, such as the FLIR ONE ™ device (FLIR systems, Wilsonville, Ore), can be attached to a smartphone to capture thermal images of a free flap, enabling the detection of temperature differences with high sensitivity. These images can be easily transmitted to healthcare providers for evaluation and early identification of flap failure. While this device has primarily been used by trained operators in the peri-operative setting for DIEP flap reconstruction, advancements in technology and reduced costs hold the potential for future remote use by patients[78]. However, it is important to note that this device is influenced by external factors such as vasoconstriction, warming blankets, or low ambient temperature, which may impact its accuracy.

Tissue oximetry
Tissue oximetry utilizes both near-infrared spectroscopy (NIRS) (wavelength: 800-2,500 nanometers) and visible light (wavelength: 40-700 nanometers) to non-invasively measure flap perfusion[79-83]. Examples of tissue oximeters commonly used in the post-operative setting include Spectros T-Stat (Houston, TX, USA) and ViOptix T.Ox (Newark, CA, USA) [Figure 1A]. The functioning principle of most oximetry systems follows a standard pattern: the oximeter devices emit light towards the flap tissue, a portion of which is absorbed by the blood. The remaining light is reflected and captured by the sensors in the oximeter. Oxygenated and deoxygenated blood reflect and emit light differently, and the oximeter probes utilize these properties to estimate the percentage of oxygenated and deoxygenated hemoglobin within the underlying tissue[13,69]. A decrease in tissue oxygenation detected by NIRS has shown high specificity and sensitivity in
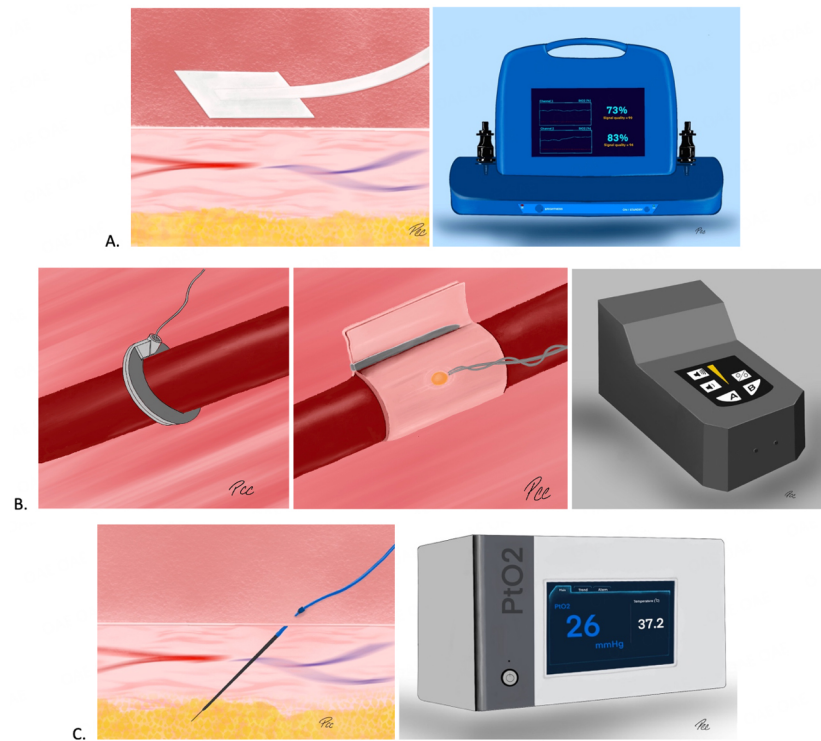
Figure 1. Types of non-invasive and invasive techniques used for flap monitoring. (A): Example of a non-invasive tissue oximetry device; (B): Example of an invasive venous coupler and implantable Doppler monitoring device; (C): Example of an invasive transcutaneous oxygen tension monitoring device.

detecting flap failure[84]. However, conflicting reports regarding time-based trends in post-operative flap oximetry exist, with some observing transient decreases, increases, or stable flap oxygenation. These trends may be attributed to fluctuations in hemodynamic status (i.e., pulse oximetry) rather than perfusion status[85].

Tissue oximetry devices serve as valuable adjuncts for flap monitoring due to their high portability, user-friendliness, and ability to provide continuous monitoring. Rather than focusing on absolute values, observing the individual oximetry trend of a flap provides greater insight into perfusion. It is important to note that while oximetry indicates organ tissue oxygenation, which directly reflects flap viability as opposed to vascular patency[80], there can be delays in detection of up to 1-5 h[86]. Additionally, environmental light and variations in skin tones can potentially interfere with accurate readings[40-41,87]. In a recent study involving over 1,000 free flaps for breast reconstruction, tissue oximetry offered no benefit over clinical judgment, although other reports present contradictory evidence[88,89]. Bai *et al.* conducted experiments using porcine models to test the use of NIRS in flaps without cutaneous paddles. NIRS probes were buried into muscle tissue to provide continuous monitoring of local tissue oxygen saturation, demonstrating the capability of heat convection probes to detect changes in tissue microcirculatory blood flow[43,90].

Implementation of tissue oximetry for routine monitoring incurs additional costs, with equipment expenses amounting to $16,500 and disposable sensor costs of $150 per unit[13]. These initial costs must be weighed against the estimated savings, which have been reported to reach as high as $1,667 with the utilization of NIRS monitoring protocols in DIEP flap reconstruction[91].

Invasive techniques

Invasive techniques for free flap monitoring are utilized for buried flaps when surface monitoring is not feasible. An ideal implantable device should possess the following characteristics: (1) enable continuous real-time monitoring of anastomotic patency; (2) reliably distinguish between arterial and venous occlusions; and (3) be applicable for monitoring both cutaneous and buried flaps. Various devices have been developed for invasive flap monitoring and ongoing research focuses on device refinement[42-47]. Current electronic flap monitoring techniques offer qualitative and quantitative information on flap perfusion, including flow patterns and quality[48-50]. However, there are limitations associated with the use of invasive monitoring techniques, such as the requirement for expert interpretation of results, inadequate equipment designs and potential malfunction, and high costs[48].

Implantable Doppler & venous coupler

Swartz *et al.* were the first to publish on the utilization of an implantable probe for continuous monitoring of microvascular anastomoses[92]. Their study employed a 20-MHz ultrasonic Doppler probe encased in a silicone sleeve positioned distal to an anastomosis, demonstrating the probe's effectiveness in monitoring patency and occlusion up to 4 weeks post-operatively[92]. This system, now referred to as the Cook-Swartz implantable Doppler (Cook Medical®, Ireland), has since become a valuable tool in clinical post-operative monitoring, particularly for buried flaps, such as those in nipple-sparing mastectomy procedures [Figure 1B]. Apart from the Cook-Swartz implantable Doppler used in buried flaps, an external transcutaneous Doppler signal can be marked on the mastectomy skin intra-operatively, following temporary clamping of the flap vascular pedicle, to minimize potential signals confusion between the mastectomy skin and the flap. In 1994, Swartz *et al.* discovered that Cook monitoring of venous anastomoses exhibited greater sensitivity to both venous and arterial thrombosis compared to solely detecting arterial anastomoses[92,93]. Since its introduction, there have been numerous advancements aimed at enhancing the monitoring of capabilities of Cook Doppler devices, which heavily rely on their positioning. These improvements encompass non-attachment around a venous pedicle, microclip fixation, suture fixation, and elongation of the silicone cuff. The success of these developments has varied, and their implementation may lead to prolonged operating times and necessitate technical expertise to ensure proper intraoperative placement[94,95]. Additionally, complications associated with Cook Dopplers include retained wires, pedicle laceration during extraction, and signal interruption due to clot formation around the probes[96].

The Flow Coupler is an additional invasive post-operative monitoring device designed to detect the patency of microsurgical anastomoses [Figure 1B]. Developed by Synovis Life Technologies in 2010, this device consists of a removable 20-MHz Doppler that provides real-time data on vessel patency. Preliminary data suggests that the Flow Coupler is both effective and reliable. However, studies comparing the results of the Cook-Swartz implantable Doppler and the Synovis Flow Coupler have not identified any significant differences in false positive or false negative results, or the need for salvage procedures[97]. The Flow Coupler may have a higher false positive rate and a higher incidence of vascular thrombotic events compared to non-flow coupler devices[98]. A pooled meta-analysis revealed that the use of a Cook-Swartz Doppler in combination with clinical monitoring is associated with significantly higher rates of flap survival but also increased Incidence of false positive results[96]. When compared to microdialysis, the implantable Cook-Swartz Doppler demonstrated earlier detection of flap compromise by 60 min and reduced time to re-exploration compared to external Doppler monitoring[99,100].

Transcutaneous oxygen tension monitoring

Tissue oxygen tension monitoring is a commonly used invasive method to assess flap perfusion and viability [Figure 1C][101]. This technique involves the use of probes that compare the partial pressure gradient

between oxygen delivered at the capillary level and mitochondrial consumption, providing a direct estimation of oxygen availability at the cellular level[102,103]. To achieve tissue oxygen tension monitoring, an implantable probe and microcatheter are typically used, with the microcatheter containing an electrode functioning as an oxygen sensor[104]. When the apparatus is placed in the flap, it measures the reduction of molecular oxygen using a cathode and polarized circuit[101,105]. Rapid declines in oxygen tension detected by these sensors indicate potential vascular compromise[106].

Oxygen tension monitoring devices offer real-time measurements of oxygenation, allowing for trend analysis over time. These measurements are easily understandable by all members of the care team and are considered highly sensitive indicators of end-organ tissue perfusion[107-109]. However, these devices require invasive procedures for placement and removal of probes, which carries the risk of flap infection. Furthermore, the temperature calibration of probes makes them susceptible to the influence of external environmental factors and subtle temperature variations within the flap. Consequently, some authors have suggested that these systems may be more prone to bias and could benefit from the integration of other flap monitoring approaches, particularly in cases involving large areas of skin or significant temperature gradients within the flap[101,110].

Fluorescence imaging

Fluorescein angiography was one of the early applications of fluorescence in measuring flap perfusion[111]. Depending on the specific use case, different fluorophores can be leveraged to monitor perfusion quality and flap viability. Indocyanine green fluorescence angiography (ICG-FA) has been extensively used for peri-operative assessment of anastomotic patency and has found applications in various fields, such as cardiac function monitoring, liver function testing, neurosurgery, and ophthalmology. As a non-toxic, water-soluble dye with a half-life of 3-4 min, ICG can be safely injected into patients to visualize microvascular patency and tissue perfusion. Adelsberger *et al.* conducted a study involving 210 free flaps to assess vascular thromboses post-operatively. They used a handheld infrared camera in a dark room to visualize the distribution of the dye after injection over a 4-hour interval for the first 72 h[112]. The combination of ICG-FA and clinical examination yielded an 85% success rate in detecting vascular thromboses. Revision rates decreased from 19% to 12%, with a false negative revision rate of 4.8% over a span of 3 years, accounting for a training and habituation period. Others have combined ICG injection with scanning of flap using a near-infrared camera with an additional pinprick test to evaluate perfusion status by fluorescent imaging of bleeding. This approach facilitates the need for repeated pinpricks and may lead to subsequent complications, such as hematoma. However, it is particularly useful in patients with questionable perfusion[113]. Hitier *et al.* determined that intraoperative fluorescence after anastomosis to the recipient vessels serves as a reliable predictor of post-operative flap viability, capable of indicating abnormal values 16 hours prior to clinical evidence of flap failure using fluorescence signal thresholds[114]. Despite its usefulness, ICG-FA has certain limitations. It does not allow for continuous monitoring and requires repeat injections. Exploring other fluorophores with increased circulation time may enable continuous monitoring and provide activation at different wavelengths.

Other monitoring techniques

Given the significant advancements in post-operative monitoring techniques for autologous breast reconstruction proven to have a high sensitivity and specificity, there has been a shift away from more outdated and costly monitoring techniques. These include the use of biochemical markers, microdialysis, technetium-99m sestamibi scintigraphy, and perfusion-weighted MRI. While we include them here for a comprehensive perspective, it is important to note their limitations in terms of invasiveness, cost, and lack of continuous monitoring.

Biochemical markers
Using a femoral vessel anastomosis rodent model, Su *et al.* reported in 1982 that both venous and arterial occlusion decreased tissue glucose content and increased lactate content. Venous occlusion was found to have a more detrimental effect on flap survival[115]. The theory behind this observation suggests that vessel occlusion impairs perfusion, resulting in decreased tissue oxygenation and glucose delivery, leading to a shift from aerobic to anaerobic metabolism[116-118].

Since then, tissue biomarkers such as glucose with or without lactate have been successfully used for flap monitoring in the clinical setting[119-122]. These biomarkers have been utilized at different threshold values and rates of change to indicate venous occlusion, showing variable sensitivity and specificity. Measurement of flap tissue glucose levels is a simple, inexpensive, and rapid option for post-operative flap monitoring compared to other techniques[13]. However, the efficacy of glucose measurements in detecting arterial occlusion and in diabetic patients is limited, and this technique lacks applicability in buried flaps[123-125].

Microdialysis
Microdialysis has been employed as a method for microinvasive monitoring of flap ischemia in various flap types, including myocutaneous, buried flaps and TRAM flaps[126-129]. This technique involves a double-lumen catheter with a semipermeable membrane at the end, which draws fluid from the flap through the membrane into the catheter. By continuously assessing small molecules in the dialysate, such as glucose, lactate, pyruvate, and glycerol, microdialysis provides a measure of the flap's metabolic activity. These values can be compared values to a baseline value or ratios, non-flap tissue away from the operative site, or reference values. The analysis of the interstitial fluid contents allows for flap examination without the need for direct clinical examination and can potentially detect ischemia one to two hours before clinical evidence of flap failure[130]. This technique is limited by its high cost and relatively high false-positive rate. Additionally, widespread adoption is restricted by the requirement for a skilled nursing team and clinical familiarity with microdialysis.

Technetium-99m sestamibi scintigraphy
Technetium-99m (99mTc) sestamibi, a metabolically inactive radionuclide, is injected and measured by scintigraphy to visualize areas of tissue hypoperfusion and evaluate microvascular anastomotic patency. It has been employed to assess free muscle flap viability, particularly in detecting a delayed secondary thrombosis caused by microemboli, which may not be evident using other techniques relying on more obvious signs[131-133]. Additionally, this technique permits visualization of partial necrosis, providing important information of surgical significance in the case of future surgical debridement[131].

Perfusion-weighted MRI
Several reports have described the use of contrast-enhanced magnetic resonance imaging (MRI) as a method for analyzing flap perfusion, with parameters optimized for vascular contrast uptake[134,135]. Compromised flaps exhibit significantly reduced signal intensity on MRI[134,135]. Perfusion-weighted MRI can assess the overall perfusion of the entire free flap. The drawbacks of this technique are mostly resource-related: the financial and time-based costs of MRIs are high. Additionally, perfusion-weighted MRI does not directly evaluate vascular pathology and necessitates specialized support staff throughout the process.

Future directions
In the past 40 years, post-operative flap monitoring technologies have advanced to provide continuous, remote, highly sensitive, and non-invasive options for surgeons. Lee *et al.* developed a new dual-camera flap monitoring system that combines mask region-based convolutional neural networks in the visible-light

system with infrared systems to address lower image resolution challenges posed by illumination changes and patient movement[136,137]. This study demonstrated earlier detection of vascular congestion compared to manual observation. Kim *et al.* utilized a novel negative pressure wound therapy technique using a transparent film to monitor the entire flap, allowing for the examination of flap color changes, capillary refilling status, and flap warmth without missing any portions of the flap[30]. This technique has been shown to reduce monitoring time and costs[30]. Videocapillaroscopy technology shows further promise in evaluating circulatory changes on the skin surfaces of free flaps while deliberately clamping pedicle vessels[138]. Bucknor *et al.* described a novel, non-invasive, optical oxygen-sensing liquid bandage for post-operative monitoring in autologous breast reconstruction[139]. This technique uses a camera to continuously capture the intensity of oxygen phosphorescence and fluorescence. Hummelink *et al.* used a "free flap patch" adherent to a flap to continuously measure temperature and tissue saturation[140]. The development of novel, patient-friendly wearable wireless monitors is ongoing, promising rapid and real-time insights into tissue perfusion.

CONCLUSION

Careful post-operative monitoring of free flaps following breast reconstructive surgery is crucial for determining procedural success. While the clinical examination remains the gold standard for post-operative flap monitoring, various adjuncts exist to complement and enhance our understanding of flap perfusion.

DECLARATIONS

Authors' contributions
Made substantial contributions to the conception and design of the study and performed data analysis and interpretation: Cevallos PC, Najafali D, Johnstone TM
Performed data acquisition, as well as provided administrative, technical, and material support: Borrelli MR, Manrique OJ, Lee GK, Nazerali RS

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All authors declared that there are no conflicts of interest.

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