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Flap Monitoring: What We Know and What Is To Come

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Abstract

Microsurgical free tissue transfer is a cornerstone of modern reconstructive surgery, offering high success rates in restoring complex defects. However, free flap failure, though infrequent, remains a serious complication associated with increased morbidity, prolonged hospitalization, and limited secondary reconstructive options. Early detection of vascular compromise is critical to maximizing flap salvage potential. Consequently, flap monitoring has become an essential component of postoperative care. This review provides a comprehensive overview of current methods used in free flap monitoring, with a focus on their clinical utility, advantages, limitations, and evidence base. Noninvasive techniques—including clinical examination, handheld Doppler, temperature assessment, infrared thermography, near-infrared spectroscopy, laser Doppler flowmetry, and smartphone-integrated tools—are widely used due to their simplicity and ease of application. In contrast, invasive methods such as implantable Doppler probes, indocyanine green angiography, microdialysis, and biochemical or bioimpedance-based sensors offer more direct or sensitive measures of perfusion but often involve higher cost, technical expertise, or limited accessibility. Despite ongoing technological advancements, clinical monitoring remains the gold standard due to its reliability, accessibility, and cost-effectiveness. Nevertheless, adjunctive tools can improve diagnostic accuracy, particularly in buried flaps or ambiguous cases. A tailored, multimodal approach—balancing invasiveness, accuracy, and feasibility—may optimize outcomes in free flap surgery.

Keywords: Free flap, microsurgery, monitarization, technology

Introduction

Microsurgical tissue transfer, also known as free flap surgery or free tissue transfer, involves the transplantation of tissue from one part of the body to another using microsurgical techniques. This procedure is widely employed to reconstruct complex defects in various anatomical regions, including the head and neck, extremities, and trunk. During free flap surgery, tissue with suitable vascular pedicles is harvested and transferred to a recipient site, where microvascular anastomosis is performed to reestablish circulation. Depending on the clinical indication, composite tissue—such as nerves or bone—can be included to restore sensory, motor, or structural integrity.

The success of microsurgical free flaps relies heavily on continuous arterial inflow and venous outflow until neovascularization is established. Despite reported success rates exceeding 95%, flap loss remains the most feared complication, potentially leading to increased morbidity, prolonged hospitalization, and limited reconstructive options. The clinical spectrum of perfusion compromise ranges from fully viable flaps to partial or complete necrosis, often requiring debridement.[1] Venous thrombosis is the most common cause of flap failure, typically presenting within the first 48 hours, whereas arterial thrombosis usually occurs within the first 24 hours (Figure 1).[1]

Prompt detection of vascular compromise is critical for successful flap salvage. Ischemia-induced endothelial damage and microthrombi formation can result in the "no-reflow" phenomenon, where tissue cannot be reperfused even after surgical revision.[2] Some studies report no flap survival after more than 12 hours of ischemia, emphasizing the importance of early identification and intervention.

Although numerous methods for flap monitoring have been investigated, none has yet surpassed clinical examination, which remains the gold standard. Most centers implement intensive monitoring protocols during the first 72 hours—when the risk of vascular compromise is highest—and

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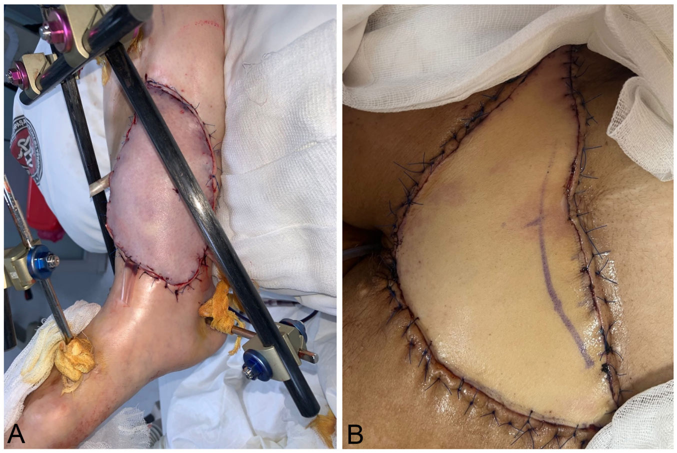

Figure 1. A free anterolateral thigh flap on the left leg showing signs of venous insufficiency (purple color, congestion, and bleeding around the suture lines) (A) and a free latissimus dorsi musculocutaneous flap showing signs of arterial insufficiency (paleness, loss of turgor, and dusky areas indicating perfusion loss) (B).

gradually reduce the frequency thereafter. The ideal monitoring method should be noninvasive, reliable, fast, applicable to all flap types, easy to use, cost-effective, and feasible for continuous use.[3] Monitoring techniques are commonly categorized by invasiveness (invasive vs. noninvasive), a classification widely used in the literature (Table 1).

This review aims to provide a comprehensive overview of current free flap monitoring techniques, their advantages and limitations, and their role in improving flap survival outcomes.

Noninvasive Methods

Clinical Examination

Clinical monitoring remains the gold standard for assessing free flap viability postoperatively due to its simplicity, immediacy, and cost-effectiveness. It includes the serial evaluation of flap color, capillary refill time, skin temperature, turgor, and the bleeding response to pinprick. These parameters offer direct insight into the vascular status of the flap without requiring specialized equipment. A venous congested flap typically bleeds from the suture margins, appears pink-purple in color with a capillary refill of less than 2 seconds, while arterial insufficiency presents as a dusky flap with a long capillary refill and no brisk bleeding after pinprick. When performed by experienced clinicians, clinical assessment has high sensitivity for detecting early compromise. However, limitations include inter-observer variability, and it is limited in buried or inaccessible flaps. Adding a skin paddle to the buried flap adds on the a cutaneous component, enabling clinical assessment of perfusion through visible skin. This is particularly useful when the primary flap tissue is not externally accessible.[4]

Table 1. Frequent methods of flap monitoring

Technique	Type	Principle	Advantages	Limitations
Clinical examination	Noninvasive	Visual/tactile parameters (color, refill, turgor)	Simple, cost-effective, universal	Subjective, not usable for buried flaps
Handheld Doppler	Noninvasive	Audible detection of superficial flow	Easy to use, portable	Superficial only, false positives
Temperature monitoring	Noninvasive	Surface temperature imaging	Quick and accessible	Not medical-grade, ambient-sensitive
Pulse oximetry	Noninvasive	O_2 saturation via light absorption	Inexpensive, real-time	Misses venous congestion, detachment risk
Color Doppler ultrasonography	Noninvasive	Flow visualization in vessels	Objective, smartphone-compatible	Requires experience, learning curve
Near-infrared spectroscopy (NIRS)	Noninvasive	Tissue StO_2 via NIR light	Continuous, operator-free	Costly, variable thresholds
Hyperspectral imaging (HSI)	Noninvasive	Spectral mapping of tissue oxygenation	High-resolution, arterial/venous distinction	Ambient light dependent, not continuous
Laser Doppler flowmetry	Noninvasive	Microcirculation via light scatter	Dynamic blood flow data	Trend-based, not for buried flaps
Implantable Doppler	Invasive	Ultrasound flow via internal probe	Continuous for buried flaps	Malposition, infection, needs removal
Flow coupler	Invasive	Ultrasound + vessel coupling	Specific, real-time flow data	Can't use in end-to-side anastomoses
Fluorescence imaging (ICG)	Invasive	Perfusion via NIR fluorescence	Intraoperative mapping	High cost, intermittent
Microdialysis	Invasive	Metabolite sampling (lactate, glucose)	Early ischemia detection	Expensive, false positives
pH monitoring	Invasive	Acidosis as ischemia marker	Simple, cost-effective	Inconsistent, variable accuracy
Wireless Doppler	Invasive	Signal transmission without wire	Less infection, continuous	Availability, still under validation
Bioresorbable sensors	Invasive	Dissolvable sensors	No removal needed	Early-stage, limited data
AI-based monitoring	Variable	Predictive analytics from sensors	Early failure prediction	Needs large datasets

NIR, Near infrared.

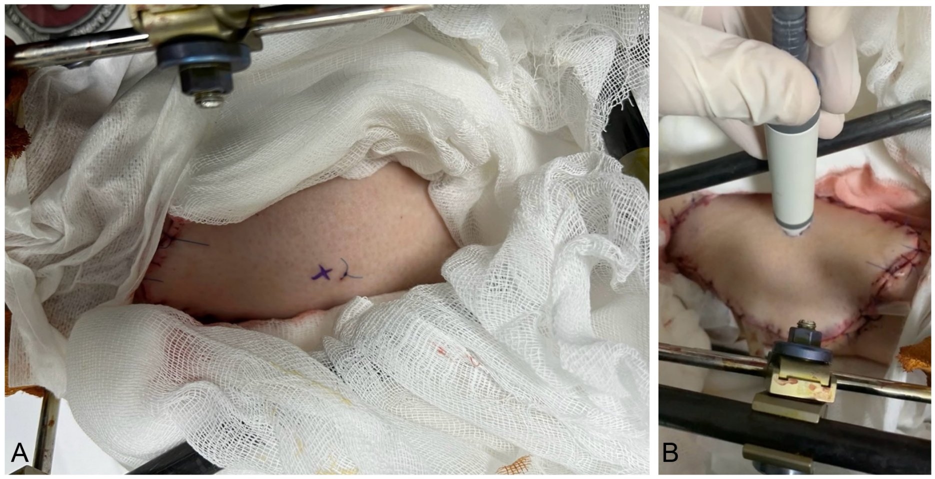

Figure 2. An anterolateral thigh flap with postoperatively determined Doppler point marked with a temporary suture (A). Doppler probe and evaluation of perfusion signals (B).

Handheld Doppler

Handheld acoustic Doppler sonography (ADS) is another commonly used noninvasive method (Figure 2). While not sufficient as a standalone tool, it is frequently combined with clinical observation. It detects blood flow by identifying audible signals from underlying vessels. However, it is limited to superficial vessels and may not detect flow in deeper or buried flaps because the probe only detects signals within its frequency range. Moreover, it can produce false reassurance by picking up signals from nearby arteries unrelated to the flap's vascular pedicle. The combined use of clinical examination and ADS yields reported success rates between 85% and 95%.[5] Monitoring is typically performed by nurses or residents, and digital tools such as photography or video recordings may support documentation and communication.

Temperature Monitoring

Temperature monitoring is a valuable adjunct for free flap surveillance. A temperature difference of more than 3°C between the flap and adjacent normal skin suggests arterial compromise, while a 1-2°C difference may indicate venous congestion.[4] Despite fluctuations in surface temperature, infrared thermometry, and thermography have shown promise in detecting vascular complications. Smartphone-integrated thermal imaging devices such as FLIR One® have made bedside assessment more accessible (Figure 3). However, FLIR is not a medical-grade device and its readings can be influenced by ambient temperature and lighting conditions. While it has proven useful in perforator mapping during preoperative planning, its reliability for routine postoperative flap monitoring remains limited according to recent literature. Furthermore, interpretation without clinical correlation increases the risk of misdiagnosis.[6]

Pulse Oximetry

Pulse oximetry is a noninvasive technique that measures arterial oxygen saturation (SaO_2) using red and infrared light absorption. It is especially useful for monitoring digital replantations or toe-to-hand transfers, where probes can be applied directly (Figure 4).[7] Studies suggest that oxygen desaturation may precede clinical signs of vascular compromise. Comparative monitoring using a second probe on unaffected tissue allows for inexpensive, real-time perfusion assessment.[8] However, pulse oximetry has notable limitations: it may fail to detect venous congestion, the probe can become dislodged with patient movement or moisture, and on small flaps, the sensor itself may obscure the surgical site, hindering visual clinical evaluation.

Laser Doppler Flowmetry

Laser Doppler flowmetry (LDF) evaluates microcirculation in real time by measuring changes in light scattered by moving red blood cells. It provides objective, dynamic data on relative blood flow up to 8 mm deep in tissue. Systems combining LDF with white-light spectrometry (e.g., O2C device) may distinguish arterial from venous complications,[9,10] though more evidence is needed to confirm benefits in flap salvage.

Limitations include the inability to monitor buried flaps, high cost, and reliance on trend interpretation rather than absolute values. While some retrospective studies report improved salvage rates, the findings are inconsistent.

Color Doppler Ultrasonography

Color Doppler ultrasonography (CDUS) visualizes blood flow in anastomosed vessels and is useful for evaluating buried flaps, such as in facial reanimation, osseous reconstructions, or jejunal free flaps.[11] It provides objective flow data but requires

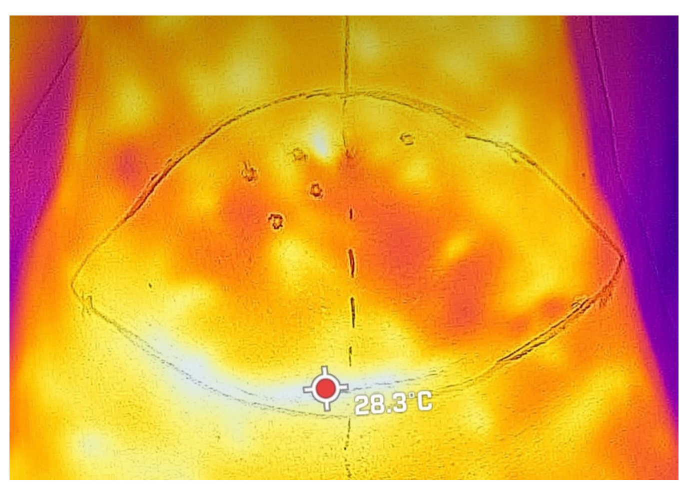

Figure 3. Determination of perforators on a planned deep inferior epigastric artery perforator flap for breast reconstruction using FLIROne thermal imaging.

Figure 4. Evaluation of perfusion of the distal extremity following revascularization at the humeral and elbow levels with pulse oximetry.

expensive equipment and trained personnel, often limiting bedside or intraoperative use.[12] Studies have shown that CDUS may not detect early vascular occlusion but can be a valuable adjunct in equivocal cases.[13,14] Recent innovations, such as handheld CDUS devices like Clarius™, allow real-time visualization via smartphone applications, greatly enhancing portability and accessibility in clinical settings. While these tools are more user-friendly, they still require a learning curve to accurately interpret flow patterns.

Near-Infrared Spectroscopy

Near-infrared spectroscopy (NIRS) measures tissue oxygen saturation (StO_2) by analyzing differential absorption of near-infrared light by oxy- and deoxyhemoglobin. It enables continuous, non-invasive monitoring and is operator-independent, making it suitable for remote applications. Reported sensitivity and specificity exceed 99% for detecting flap compromise. However, StO_2 thresholds may vary with body mass index, age, and other factors, and some studies found no superiority over standard Doppler.[15] High device and consumable costs and limitations in buried flap monitoring are additional challenges.[16]

Hyperspectral Imaging

Hyperspectral imaging analyzes tissue reflectance across a range of wavelengths to produce high-resolution color-coded maps of hemoglobin saturation and perfusion indices.[17] It distinguishes between arterial and venous compromise with similar accuracy to NIRS.[18] Its limitations include dependence on ambient light, lack of continuous monitoring, and relatively high initial cost. Hyperspectral imaging may also be challenging to use in tremor-prone elderly patients during image capture.[19]

Multispectral Imaging

Multispectral spatial frequency domain imaging can detect changes in tissue oxygenation before visible signs of ischemia appear. Animal and early human studies suggest high accuracy and feasibility.[20] Luminescence ratiometric oxygen imaging, which

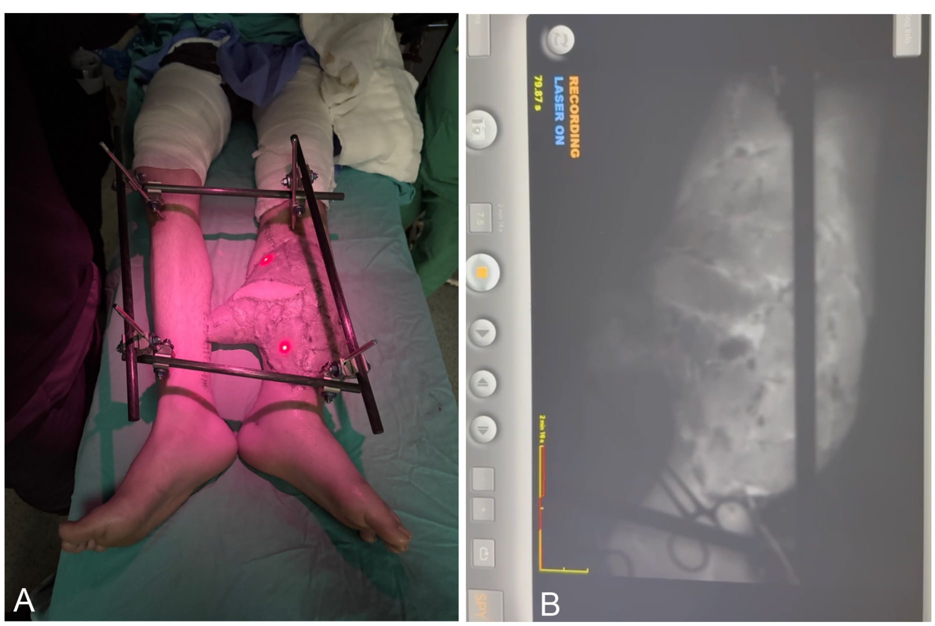

Figure 5. Perfusion assessment of a performed latissimus dorsi free flap on the lower extremity, with vascular supply coming from the contralateral leg under SPYElite indocyanine green angiography (A). The flap is well perfused from the adapted leg, which enables secure pedicle division from the contralateral leg (B).

assesses transdermal oxygen consumption, has also shown promise in distinguishing well perfused from poorly perfused flaps.[21]

Telemedicine and Smartphone Applications

Digital photography allows for remote flap monitoring, facilitating timely communication and decision-making. Studies by Hwang and Mun[22] reported improved salvage rates and shorter re-exploration times using secure messaging systems. Smartphone apps designed to analyze color variations in digital images are also under development.[23] Despite potential benefits, concerns about technical errors, cost, misdiagnosis, and patient privacy must be addressed before widespread adoption.

Eulerian Video Magnification

Eulerian video magnification is a novel software-based approach developed by Massachusetts Institute of Technology (MIT) that amplifies subtle color changes in video frames to visualize physiologic signals such as pulse and perfusion.[24] It enables clinicians to assess real-time perfusion using standard video footage and has been proposed as an innovative tool for flap monitoring.

Photoplethysmography

Photoplethysmography uses optical sensors to detect pulsatile changes in blood volume. By analyzing the differential absorption of red and infrared light, it provides real-time information on arterial oxygenation. It has demonstrated high sensitivity and specificity and may be particularly useful when other methods yield inconclusive results.[25]

Sidestream Dark Field Imaging

SDF imaging allows direct visualization of microcirculation at the capillary level using specialized LED-based optics. It is noninvasive and easy to interpret. While currently limited to animal models and isolated clinical reports, it may offer advantages in patients with pigmented skin where capillary refill is difficult to assess visually.[26]

Confocal Microscopy

Confocal microscopy provides high-resolution optical sectioning of tissue and may help distinguish between venous and arterial obstruction based on capillary morphology. Despite its potential, no clinical studies currently support its routine use in flap monitoring.[27]

Orthogonal Polarized Light Imaging

This method uses polarized green light to image superficial microvasculature. Studies in animal models suggest it may predict flap necrosis, but clinical data are lacking.[28]

Invasive Methods

While noninvasive methods remain the mainstay in routine free flap monitoring, several invasive techniques have been developed to provide more sensitive or direct evaluation of flap perfusion, especially in cases of buried flaps or when high-resolution real-time data is required.

Implantable Doppler Probes and Flow Couplers

First described by Swartz in 1988, implantable Doppler probes consist of a piezoelectric crystal embedded in a silicone cuff wrapped around a vessel—typically a vein or artery—at the anastomosis site.[29] The probe provides continuous signal output and is particularly useful for monitoring buried flaps.

While initial applications focused on arterial placement, later studies demonstrated greater sensitivity when probes were applied to venous anastomoses. Arterial probes detect arterial occlusion instantly but show a delayed response in venous thrombosis, which venous probes can detect more promptly. The externalized probe wire is sutured to the skin and connected to a bedside monitor. Removal is performed by applying gentle traction (typically 50 grams) on postoperative days 5-10.[30] However, these devices have several limitations: malpositioning can cause false-negative results, wire breakage may lead to false reassurance or device failure, and the externalized wire introduces a potential infection risk. Additionally, the need for probe removal adds another postoperative step.

Flow couplers combine microvascular coupling devices with embedded ultrasonic Doppler sensors. Their cost is comparable to that of separate coupler and probe systems and offers real-time, vessel-specific perfusion data. However, they cannot be used in end-to-side anastomoses, limiting their versatility in complex reconstructions.

Fluorescence-Based Imaging

First explored in flap viability in the 1940s, fluorescence-based imaging has since evolved with the adoption of indocyanine green (ICG) angiography (e.g., SPY Elite system, Figure 5). Indocyanine green binds tightly to plasma proteins and emits fluorescence when exposed to near-infrared light, enabling real-time visualization of perfusion.[31]

Due to its short plasma half-life (3-5 minutes), ICG can be administered multiple times intraoperatively or postoperatively without toxic accumulation. Applications include perfusion mapping, flap design, and identification of ischemic tissue, aiding decisions regarding revision or delayed reconstruction. Limitations include high cost, limited availability for continuous monitoring, and a rare risk of allergic reaction.[31]

Microdialysis

Microdialysis employs a double-lumen catheter with a semipermeable membrane to monitor flap metabolism.[32] It detects ischemia by analyzing interstitial concentrations of glucose, lactate, pyruvate, and glycerol, with characteristic ischemic profiles including elevated lactate and high lactate/glucose or lactate/pyruvate ratios. The method can detect ischemic events up to 2 hours before clinical signs appear, including in buried flaps. However, it is costly, and false positives may occur.[32]

Biochemical Monitoring

Glucose and lactate concentrations in flap interstitial fluid can be simple, cost-effective indicators of vascular compromise. A glucose level below 3.85 mmol/L and lactate above 6.4 mmol/L have shown high sensitivity and specificity in detecting pedicle occlusion.[33,34] Other studies have explored glucose/systemic glucose ratios and lactate/glucose indices to diagnose arterial and venous thrombosis.

Impedance Plethysmography

Impedance monitoring applies alternating current through the flap and measures voltage changes to assess blood volume and pulsatile flow. Animal studies have reported accurate, real-time identification of vascular compromise, but clinical data remain lacking, and its invasive nature limits routine application.[35]

Nuclear Imaging

Various isotopes (e.g., 85Kr, 133Xe, 99mTc) have been evaluated for direct perfusion measurement via scintigraphy or PET.[36,37]

Despite their sensitivity, limited access, radiation exposure, and delays between isotope injection and imaging reduce clinical utility in early flap salvage.[38] PET imaging, using radiolabeled glucose, has been proposed as an adjunct when clinical access to the flap is limited. However, logistical and economic limitations, particularly in the early postoperative phase, restrict its use to selected cases.[38]

Tissue Carbon Dioxide Monitoring

Transcutaneous carbon dioxide ($TcPCO_2$) and oxygen pressure ($TcPO_2$) measurements have been suggested as potential early indicators of flap failure.[39] However, most systems are invasive, and clinical data supporting their use are limited.

Hydrogen Clearance

Hydrogen clearance measures tissue perfusion by tracking changes in electrical impedance due to hydrogen diffusion. A small clinical study ($n = 9$) demonstrated earlier detection of flow changes than clinical assessment and the ability to distinguish arterial from venous compromise.[40] Further studies are required to validate its impact on clinical outcomes.

Contrast-Enhanced Ultrasonography

The injection of microbubble contrast agents such as sulfur hexafluoride (e.g., SonoVue) during ultrasonography allows real-time perfusion imaging with software-based quantification (e.g., QONTRAST).[41] Despite potential drawbacks, issues include the need for repeated injections, additional personnel, high cost, and limited data.

Tissue pH Monitoring

pH monitoring has been explored as an early ischemia marker since the 1980s, with rapid decreases in pH correlating with arterial or venous occlusion.[42] Although simple and inexpensive, inconsistent accuracy and the lack of standardized equipment limit its clinical adoption.

Recent Advancements

The field of free flap monitoring has undergone substantial evolution in recent years, marked by the integration of advanced sensor technologies and intelligent monitoring systems. These developments aim to mitigate the limitations of traditional clinical assessment methods, which often rely on subjective observations such as skin color, capillary refill, and temperature.

One of the most promising innovations is the deployment of miniaturized and wearable biosensors, which enable continuous and real-time assessment of flap viability. Recent advancements in NIRS, as exemplified by self-calibrated devices, allow for reliable quantification of tissue oxygenation (StO_2) irrespective of patient phenotypes such as skin tone and thickness.[43,44] These sensors are further optimized with Bluetooth low-energy technology, providing real-time feedback via mobile platforms to facilitate immediate clinical interventions. Wireless Doppler devices, which transmit flow data without externalized wires, have emerged as a less invasive alternative to traditional implantable Dopplers, reducing patient discomfort and infection risk. In parallel, bioresorbable implantable sensors—designed to naturally degrade after completing their function—eliminate the need for device removal.

Additionally, bioelectrical impedance analysis (BIA) has emerged as a noninvasive and real-time method to detect vascular compromise in flaps.[45] Wireless BIA systems have demonstrated efficacy in animal models, showing significant bioimpedance variations following arterial or venous occlusion, suggesting their potential for early detection of ischemic events.

A significant leap forward involves the application of flexible microneedle sensors integrated with dual-modulus siloxane polymers, enabling precise pH mapping of tissues. These conformable devices penetrate the skin with minimal invasiveness and provide high spatial resolution for detecting ischemic conditions through metabolic acidosis signatures.[46] Their mechanical durability and adaptability to curved surfaces position them as formidable tools for post-surgical surveillance. In addition, other biochemical markers, including lactate and pyruvate, have prompted the development of biochemical biosensors.[47]

Furthermore, multimodal wearable or implantable sensors have been developed to concurrently measure parameters such as temperature, oxygen saturation, and pH, offering a holistic view of flap physiology.[48] These systems utilize soft electronics and are designed for both intraoperative and postoperative use, addressing the critical need for continuous monitoring during the early postoperative period—a window vital for flap salvage.

Finally, the incorporation of artificial intelligence (AI) in flap monitoring holds transformative potential.[49,50] AI algorithms are being trained on datasets from sensor outputs to predict flap failure before clinical signs appear. This predictive capability not only improves diagnostic accuracy but also facilitates timely decision-making in reconstructive surgery.

Conclusion

Together, these technological advancements are redefining the landscape of flap monitoring by enhancing diagnostic precision, enabling early intervention, and ultimately improving surgical outcomes.

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Peer-review: Externally peer-reviewed.

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