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Flap Blood Glucose Level for Monitoring Flap Survival

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Abstract

Flap surgery represents a cornerstone of modern reconstructive procedures, enabling the transfer of vascularized tissue units to restore form and function in complex defects. The evolution of flap techniques traces back to early pedicled flaps used for nasal reconstruction, progressing through axial-pattern designs in the mid-20th century and culminating in the advent of microsurgical free tissue transfer. Flaps are classified according to blood supply, tissue composition, anatomical location, and method of transfer, ranging from local random-pattern flaps to intricate free flaps relying on microvascular anastomosis. Despite high success rates, vascular complications such as arterial insufficiency and venous congestion remain the leading causes of flap failure. Consequently, effective monitoring is critical for early detection and timely intervention. Traditional methods clinical examination, temperature assessment, and Doppler ultrasonography remain the standard, yet newer biochemical and sensor-based techniques have emerged to enhance accuracy. Among these, blood glucose monitoring offers a promising, objective indicator of tissue perfusion and metabolic integrity. Decreases in flap glucose levels precede visible ischemic changes, enabling early salvage interventions. Integration of glucose monitoring with microdialysis, near-infrared spectroscopy, and advanced sensor technologies may further optimize postoperative outcomes. Future research should focus on standardizing glucose thresholds, validating sensor systems, and applying AI-based predictive algorithms to improve flap survival and patient recovery.

Keywords: Flap surgery, reconstructive surgery, vascularized tissue, free flap, pedicled flap

History of Flap

A flap is a vascularized tissue unit transferred from one body part to another, defined by its specific vascular anatomy [1]. It may consist of a single tissue (skin, fascia, muscle, bone, fat, tendon, or nerve) or multiple combined tissues. When the vascular continuity is maintained, it is termed a pedicled flap; if the artery and vein are divided and re-anastomosed, it becomes a free flap, also known as free tissue transfer **[2]**.

Historical Background

The word *flap* originated from the Dutch *flappe*, meaning "something loose and attached on one side." Early flaps were pedicled, first used for nasal reconstruction [3]. Since wounds of the head, neck, and lower limbs rarely healed by secondary intention, early flaps targeted these regions. These were random-pattern flaps, lacking a defined vascular supply [4].

Von Graefe's *Rhinoplastik* (1818) advanced flap use and inspired later development of axial-pattern flaps with defined arteries during the 1950s–1960s [5]. Further progress established cutaneous territories, muscle rotation arcs, and microsurgical transplantation techniques [4]. Surgeons such as Cohen et al. [6] expanded the use of muscle and musculocutaneous flaps, forming the basis of modern reconstructive surgery.

Flap Types and Classification

Flaps are essential in reconstruction to restore form and function while maintaining intrinsic vascularity **[2].** They are categorized by several anatomical and functional criteria **[4].**

1. Based on Blood Supply

- Random-pattern flaps: Supplied by the subdermal plexus, limited to a 2 : 1 length-to-width ratio. Examples: local advancement and rotation flaps.
- Axial-pattern flaps: Based on a named artery, allowing larger and more reliable transfers, e.g., groin flap and forehead flap supplied by the supratrochlear artery [7].

2. Based on Tissue Composition

- **Cutaneous flap:** Skin ± subcutaneous tissue.
- **Fasciocutaneous flap:** Includes fascia, providing a stronger blood supply.
- **Muscle / Myocutaneous flap:** Contains muscle; used to fill dead space or treat infection.
- **Osteocutaneous flap:** Comprises bone and skin (e.g., fibula flap for mandibular reconstruction).
- **Adipofascial or fascial flap:** Fat + fascia without skin.
- **Visceral flap:** Derived from organs such as the omentum or bowel **[2].**

3. Based on Location

- **Local flap:** Adjacent to the defect includes advancement, rotation, transposition, or interpolation designs.
- **Regional flap:** Near the defect but not contiguous, often pedicled.
- **Distant flap:** From a remote site; may be pedicled or free **[7].**

4. Based on Transfer Method

- **Pedicled flap:** Retains original vascular pedicle.
- **Free flap:** Fully detached and reattached using microvascular anastomosis **[7].**

5. Based on Movement Design

- **Advancement:** Linear movement into defect.
- **Rotation:** Pivoted into defect.
- **Transposition:** Moved over intact skin.
- **Interpolation:** Crosses intervening tissue in staged fashion **[2].**

Complications of Flap Surgery

Despite advances, flap surgery carries inherent risks affecting both donor and recipient sites **[8].**

Vascular Complications

Adequate blood flow is vital for flap survival. Arterial insufficiency results from thrombosis, technical error, or compression, producing pale, cold tissue requiring urgent revision [9]. Venous congestion leads to cyanotic, swollen tissue due to obstructed drainage; surgical relief is often required [10]. Total flap failure, involving both arterial and venous compromise, necessitates debridement and re-reconstruction [11].

Infectious Complications

Infection delays healing and may threaten flap viability **[12].** Superficial infections present as erythema and discharge, managed conservatively [13], whereas deep infections involving pedicle or anastomosis require drainage and prolonged antibiotics [14]. Osteomyelitis can occur in osteocutaneous flaps, demanding aggressive therapy **[15].**

Wound Dehiscence and Breakdown

Both donor and recipient sites may suffer dehiscence due to tension or ischemia **[16].** Secondary repair may be required **[12].**

Hematoma and Seroma

Hematomas compress vascular supply, causing ischemia, while seromas delay healing and increase infection risk; both require evacuation or aspiration **[11].**

Neurological and Functional Complications

Sensory loss and neuroma formation may occur [10]. Muscle weakness follows muscle flap harvest (e.g., rectus abdominis), while prolonged immobilization causes joint stiffness and gait disturbance after bone flaps [11].

Aesthetic and Psychological Issues

Contour deformities, pigment mismatch, and hypertrophic scars may impact patient satisfaction [16, 17]. Psychological distress, including anxiety and depression, may develop, warranting counseling [14].

Systemic Complications

Extended operations increase risk of DVT/PE, cardiopulmonary strain, and sepsis, emphasizing the need for prophylactic anticoagulation and early mobilization [14, 15].

Flap-Specific Risks

Free flaps risk microvascular thrombosis; pedicled flaps may suffer tension ischemia, while perforator flaps are technically demanding [13].

Vascular Complications in Flap Surgery

Vascular compromise remains the principal threat to flap viability **[18].**

1. Arterial Insufficiency

Caused by pedicle kinking, thrombosis, or spasm, presenting as pale, cool, non-bleeding tissue with absent Doppler signal [19]**.**

2. Venous Congestion

More common than arterial issues, it manifests as cyanotic, tense flaps with rapid dark bleeding on pinprick but poor venous Doppler flow **[19].**

3. Thrombosis

Occurs mainly within 24–72 hours post-operation, due to technical errors, hypotension, or coagulation disorders **[18].**

4. Vasospasm

A transient arterial narrowing from surgical trauma or cold exposure, potentially reversible **[19].**

5. Hematoma / Seroma

Blood or serous fluid collection compresses vessels and must be promptly drained **[19].**

6. Flap Edema

Prolonged surgery or trauma elevates interstitial pressure, reducing perfusion **[19].**

Prevention and Management

Complications can be reduced by:

- **Preoperative optimization:** managing diabetes, smoking, and malnutrition **[17].**

- **Intraoperative care:** meticulous dissection and avoidance of tension.
- **Postoperative monitoring:** using Doppler or NIRS for perfusion assessment.
- **Rehabilitation:** physical therapy and psychological support **[16].**

A multidisciplinary approach combining surgical precision and vigilant postoperative care enhances flap survival and patient outcomes **[17].**

Flap Monitoring Techniques

Flap surgery is a cornerstone in reconstructive procedures, enabling transfer of vascularized tissue from a donor to a recipient site for complex anatomical restoration such as jaw or breast reconstruction. Unlike grafts, flaps retain an intact blood supply that is surgically reconnected at the recipient site **[20].** Despite advances, flap failure rates remain significant, with reported success around 95%, yet microvascular failure is costly and often irreversible. Early detection of vascular compromise is vital to improve flap salvage and survival **[7].**

Although numerous reviews exist, few studies compare experimental and clinical monitoring systems from both surgical and engineering perspectives. A comprehensive review by **Rogoń et al. [21]** categorized monitoring methods into physical examination, surface temperature, ultrasound-based metabolic, and light-based techniques. These are essential for ensuring flap vitality and early detection of complications.

Patient Monitoring Duration

The first 48 h post-surgery is the critical period for flap monitoring, during which most vascular complications occur [22]. A review of 109 studies involving 44,031 free flaps confirmed this as the optimal window for detecting thrombosis or ischemia. About 95% of circulatory issues appear within 72 h [23].

Extended observation up to one week is recommended to detect late complications. In clinical surveys, 50% of surgeons monitor flaps for 48–72 h, 33% for more than 72 h, and 16% for 24–48 h [24].

Flap Failure Detection and Monitoring Protocols

Monitoring protocols vary, but commonly involve checks every 30 min for 3 h, then hourly up to 48 h, every 2 h up to 72 h, and later every 4–8 h until discharge. Surveys show 75% of surgeons monitor flaps at ≤3 h intervals, 23% at 3–6 h, and only 2% at >6 h intervals [25].

Reduced frequency does not necessarily compromise outcomes. One study found flap compromise in 12% of cases monitored every 4 h, 8% every 8 h, and 6% every 12 h, with success rates of 92%, 93%, and 95%, respectively. Mean times for successful salvage and failure were 127 min and 192 min, respectively; the latest salvaged flap was 188 min post-thrombosis detection [26].

Clinical Monitoring Methods

Physical Examination

Clinical evaluation remains the gold standard and includes assessment of color, temperature, capillary refill, skin turgor, and bleeding. A pale, cool flap with delayed refill suggests arterial insufficiency, while a cyanotic, congested flap indicates venous obstruction. Simple needle-prick tests can assess dermal bleeding bright red and brisk in viable flaps versus dark, delayed, or absent in compromised ones [7].

Temperature Monitoring

Temperature difference ≥**2°C** between flap and adjacent skin signals possible perfusion issues. Infrared thermography offers real-time surface temperature mapping with high sensitivity but limited depth evaluation **[21].**

Biochemical and Physiologic Methods

Monitoring of **tissue oxygenation, carbon dioxide, and lactate** reflects flap metabolism.

- Surface pH below 7.3, oxygen tension <30 mmHg, or lactate >5 mmol/L suggest ischemia.

- Microdialysis allows continuous measurement of metabolites such as glycerol, glucose, and lactate-pyruvate ratio, offering an early warning of perfusion deficits **[27].**

Ultrasound-Based Techniques

Doppler ultrasonography both handheld and implantable detects flow within the vascular pedicle.

- Acoustic Doppler provides noninvasive real-time assessment but is operator-dependent.
- Implantable Doppler probes offer continuous feedback on pedicle patency, with sensitivity 91–100% and specificity 87–98%, reducing false-negative flap loss [26].
- Duplex and color Doppler further quantify flow velocity and vessel diameter, identifying early thrombotic changes.

Prediction of Flap Survival Using Blood Glucose Levels

Concept and Rationale

Predicting flap survival through blood glucose monitoring has emerged as a novel and objective method in reconstructive surgery [12]. Flap success depends primarily on adequate perfusion, as ischemia and necrosis are major causes of failure. Conventional assessments based on clinical observation or imaging may miss early metabolic alterations, whereas glucose monitoring provides a real-time biochemical marker reflecting tissue perfusion and metabolic activity [28].

In well-perfused tissues, glucose remains stable due to adequate oxygen and nutrient delivery. Conversely, in ischemic conditions, glucose uptake rises while circulating glucose within the flap declines due to impaired replenishment [33]. This reduction signals a shift toward anaerobic metabolism, preceding visible signs of compromise [30].

Intraoperative and Postoperative Applications

During free flap surgery, blood glucose measurement before and after vascular anastomosis offers immediate feedback on perfusion adequacy. A sharp post-anastomotic drop in glucose indicates insufficient inflow or incomplete connection, necessitating prompt revision [31].

Postoperatively, persistent low glucose values often signal venous congestion or arterial thrombosis [29]. Continuous or periodic glucose monitoring enables early detection and intervention whether through surgical revision or pharmacologic management significantly improving salvage rates.

Techniques of Glucose Measurement

Microdialysis

Microdialysis provides continuous interstitial glucose measurement within the flap using a microcatheter that samples tissue fluid in real time. It also tracks metabolites such as lactate, glycerol, and pyruvate, providing a metabolic profile of perfusion [28]. Although accurate, it is technically demanding and invasive, limiting routine use.

Direct Blood Sampling

Direct capillary or venous sampling from the flap offers a simpler method with less invasiveness but requires standardized timing and site protocols to ensure reproducibility [29].

Emerging Sensor Technologies

New implantable or noninvasive glucose sensors provide continuous and user-friendly monitoring. These devices use optical or electrochemical detection, offering automated alerts for perfusion decline and improved postoperative care **[28].**

Limitations and Challenges

Despite promising results, glucose-based monitoring lacks standardized thresholds defining ischemia across different flap types and patient populations. Variables such as flap composition, metabolic rate, and systemic disorders (e.g., diabetes) affect glucose interpretation [31].

In diabetic patients, altered baseline metabolism may obscure ischemic changes, requiring individualized cutoff values.

Further limitations include device calibration errors, sensor sensitivity, and absence of large multicenter validation trials [30]. Standardized protocols defining normal vs. critical glucose levels and timing intervals are needed to establish clinical reliability.

Clinical Value and Future Directions

Monitoring flap glucose provides objective, quantifiable evidence of tissue viability, complementing Doppler, near-infrared spectroscopy, and visual examination [28]. It allows early detection of ischemia often before color or temperature changes thereby enhancing flap salvage and patient outcomes.

Future work focuses on advanced implantable glucose sensors capable of wireless continuous monitoring and AI-driven predictive algorithms integrating glucose with lactate and oxygen data for automated decision support [31].

Cellular Glucose Metabolism

Overview

Glucose metabolism is central to cellular energy production, generating adenosine triphosphate (ATP) required for survival and growth . It proceeds through three main pathways: glycolysis, pentose phosphate pathway (PPP), and oxidative phosphorylation (OXPHOS), which together maintain energy and redox balance **[18].**

1. Glycolysis

Occurs in the cytoplasm, converting glucose to pyruvate with a net yield of **2 ATP** and **2 NADH** per molecule.

Key regulatory enzymes include:

- **Hexokinase/Glucokinase** – catalyze glucose phosphorylation.
- **Phosphofructokinase-1 (PFK-1)** – the rate-limiting enzyme responding to ATP and citrate levels.
- **Pyruvate kinase (PK)** – drives ATP formation from phosphoenolpyruvate **[32].**

Under anaerobic conditions, pyruvate converts to lactate, sustaining ATP generation when oxygen is limited.

2. Pentose Phosphate Pathway (PPP)

This cytosolic pathway generates NADPH for antioxidant defense and ribose-5-phosphate for nucleotide synthesis **[19].**

- The oxidative phase produces NADPH.
- The nonoxidative phase interconverts sugars for biosynthetic needs. Glucose-6-phosphate dehydrogenase (G6PD) regulates the rate-limiting step, responding to NADPH demand.

3. Oxidative Phosphorylation (OXPHOS)

In aerobic conditions, pyruvate enters mitochondria and is oxidized via the TCA cycle, generating NADH and $FADH_2$ that fuel the electron transport chain (ETC). OXPHOS produces 30–32 ATP molecules per glucose, making it the most efficient energy source [33]. Mitochondria also regulate apoptosis, calcium signaling, and ROS balance [34].

4. Regulation of Glucose Metabolism

Hormonal Control

- **Insulin** promotes glucose uptake and glycolysis while inhibiting gluconeogenesis.
- **Glucagon** and **cortisol** enhance hepatic glucose production during fasting.
- **AMPK** activates glycolysis and fatty acid oxidation during energy deprivation **[19].**

Transcriptional and Signaling Regulation

- **HIF-1** upregulates glycolytic enzymes in hypoxia.
- **NF-κB** modulates glucose metabolism during inflammation **[18].**
- **PI3K/Akt** signaling enhances GLUT4 translocation for glucose uptake.
- **mTOR** coordinates cellular growth and metabolism, linking nutrient status to glycolysis**[18].**

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