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MASTER CLASS IN PLASTIC SURGERY

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Current techniques in the post-operative monitoring of microvascular free-tissue transfers

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Abstract Accurate assessment of the perfusion of freetissue transfers has always been a challenge for surgeons undertaking microvascular reconstructive procedures. Microvascular free-tissue transfer today has a high success rate, which is partly due to the monitoring of flap circulation post-operatively. Recent advances in technology and improvements in surgical technique have led to reported success rates of between 95% and 98%. The aim of post-operative surveillance is the early recognition of flap compromise to improve chances of flap salvage and lower morbidity and mortality rates. There is extensive literature available on post-operative monitoring, and, although many techniques to assess flap perfusion have been described, a standard, reliable, universally accepted method, other than bedside clinical observation by the medical and nursing staff, remains elusive. This review outlines the current clinical and experimental flap monitoring methods available.

Key words Monitoring · Post-operative · Free flaps · Current practice

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Introduction

Accurate assessment of the perfusion of free-tissue transfers has always been a challenge for surgeons undertaking microvascular reconstructive procedures. In many cases the complexities of flap microcirculation are difficult to assess, despite all the subjective and objective examination techniques available today. This is further compounded when the free-tissue transfer is not visible for monitoring, for example, in a buried, vascularised bone graft during head and neck reconstruction.

Routine monitoring of free flaps is often undertaken by nursing staff on the ward. Junior medical staff have little experience of such monitoring. Therefore, the ideal technique of monitoring should be straightforward, and any data collected for the post-operative monitoring of these free flaps should be unambiguous and easily interpretable. An objective monitoring technique that can be easily interpreted would have immense practical benefit.

The ideal method of monitoring flap viability should satisfy the criteria proposed by Creech and Miller in 1975 [5]:

- Simple, and harmless to the patient and free flap
- Rapid, repeatable, reliable, recordable and rapidly responsive
- Accurate and inexpensive
- Objective and applicable to all kinds of flaps
- Equipped with a simple display that could alert relatively inexperienced personnel to the development of circulatory impairment

Methods used to monitor free-tissue transfers

Clinical tests

Of the techniques currently available to monitor free flaps post-operatively, clinical assessment is the most commonly used [44]. "Clinical tests" for the purpose of this review consist of the following:

- Skin colour of the flap
- Skin turgor
- Surface temperature
- Capillary refill time
- Bleeding time following pinprick

Clinical tests are cheap, non-invasive and repeatable. It must be accepted, however, that simple clinical assessment has certain limitations. There is a need for experienced interpretation. Perception of colour is markedly affected by ambient lighting [10], and transferred skin colour may also be different from that of the recipient site. Subjective assessment of surface temperature is often unreliable [19]. Even more importantly, clinical changes may be subtle, initially, and, by the time they are clinically apparent, salvage of the flap may be impossible because of irreversible tissue damage. It has been demonstrated that capillary bleeding on pinprick, in terms of colour (bright red vs cyanotic) and speed (brisk vs slow), is a particularly reliable indication of microvascular status, and some authors still believe clinical observation to be the "gold standard" [6].

Adjunctive techniques

Chemical techniques

Several chemical techniques for monitoring of free flaps have been used historically.

Fluorescein

Sodium fluorescein (resorcinol phthalein sodium, $C_{20}H_{10}Na_2O_5$) is a hygroscopic orange–red powder, readily soluble in water, which assumes an intense yellow–green colour, visible by the naked eye, when viewed under a Wood's lamp in a darkened room. It is an organic dye that is injected intravenously to monitor skin perfusion. In the 1940s, Dingwall and Lord used it to test the circulation in tubed pedicles [8], and Conway et al. confirmed this with rabbit tubed pedicles in a single animal study [4]. In a study of 285 pedicled flaps the fluorescein-injection technique predicted flap survival within a distance of 3–5 mm (McCraw et al. in 1977 [30]).

The fluorescein test involves the injection of sodium fluorescein, intravenously, at 15 mg/kg for 1 min. The dye diffuses across the capillary wall to the extracellular fluid compartment within 10–15 min but does not penetrate cells. The distribution is then observed. The result can even be photographed with a blue filter to allow a record to be kept. The technique is relatively straightforward and inexpensive but is cumbersome to perform, and allergic reactions can occur [31].

This technique is prone to subjective error in the interpretation of marginal fluorescence [26] and is only suitable for the monitoring of cutaneous free-tissue transfers. In addition, it allows only a single assessment

over 24 h, because the high dose of dye required for visual assessment stains the skin for 12–18 h.

These limitations led to the search for a technique that would improve the precision and accuracy of assessing skin flap viability and that would also permit repeated assessments of skin fluorescence post-operatively.

Silverman et al. [33] reported in 1980 the use of a fibre-optic dermofluorometer for assessment of skin fluorescence in animal models. It was subsequently demonstrated that skin fluorometry could also be used for repeated assessment of skin fluorescence, postoperatively, to allow accurate prediction of skin viability in random pattern skin flaps, island skin flaps and skin free flaps in the rabbit as well as myocutaneous flaps in the pig. Graham et al. [14] found this technique useful for monitoring finger re-plantation. More recently, in 1996 Issing and Naumann [18], utilising an animal model, concluded that fluorescein staining with computer-aided digital morphometry (CADM) represented a more precise predictor of flap survival when compared with pH and temperature monitoring. The safety of intravenous fluorescein was investigated by Morykwas in 1991 [31]; several recommendations were made:

- Fluorescein should be administered by medical personnel with the ability and equipment to carefully monitor and treat complications that might occur.
- Patients who were injected with fluorescein should have adequate intravenous access lines before administration of the drug.
- Fluorescein should be administered via an indwelling venous cannula with a running i.v. solution.
- It should be given slowly over a 5–10 min period while the patient is monitored for possible adverse effects.

It is notable that in Morykwas's study no patient suffered significant systemic sequelae or flap complications. In contrast, in another study, 10%–15% of patients complained of nausea or pain due to local extravasation of fluorescein [3]. Pruritic urticaria and oedema constituted the majority of the 0.6% adverse effects during retinal angiography [36]. During retinal angiography there is a 0.2% incidence of anaphylactic reaction to fluorescein, which includes syncope, shock, myocardial infarction and cardiac arrest.

Indocyanine green

Because of the severity of the potential side effects of fluorescein, and its unfavourable pharmacokinetic properties, another fluorescent dye, indocyanine green, with far better pharmacokinetic properties, has been investigated. Initial clinical results were promising (Eren et al., in 1995 [12]). This dye has such diverse uses as monitoring heart function [43] and guiding sentinel lymph node biopsies. Little work has been done with indocyanine green and flap monitoring. Further research is needed before it becomes a practical alternative.

Tissue pH

Monitoring of tissue pH levels is a technique that has been utilised in the post-operative assessment of free-tissue transfers. Impairment of tissue blood flow causes an increase in anaerobic metabolic products and an accumulation of acid metabolites. The resulting increased concentration of hydrogen ions causes a pH drop in the affected tissues. Subcutaneously and intramuscularly placed pH probes have been described. Raskin et al. [32] described three patients in whom there was a pH drop of 0.35 units during the first 2 h post-operatively, which led to free-flap exploration. Clinical observation alone had not yielded this diagnosis. This technique may be particularly useful for muscle flaps because their colour is difficult to observe.

Radioactive isotopes

Radioactive isotopes have been studied as a means of directly measuring tissue perfusion. The basis of the radioactive tracer techniques is centred on the Fick dilutional principle. The ideal tracer should be metabolically inert and diffuse between blood and tissue with no significant impairment (Kety, 1951 [22]). Many different isotopes have been used for assessing tissue clearance, such as ⁸⁵Kr, ¹³³Xe, ²²Na and ^{99m}Tc.

Technetium-99m

Technetium-99m sestamibi scintigraphy was studied by Aygit and Sarikaya [2] in 1999 as a non-invasive option for monitoring free muscle flap viability, but the results were initially unconvincing.

The most useful application is probably the assessment of vascularised bone grafts, using the technetium-99m bone scans during the first post-operative week. The major disadvantages were that measurements with this technique could only be repeated once per day, at most, due to remaining background radioactivity, and, like other radioactive techniques, it suffers from the costly problems of radioactive waste decontamination and unavoidable radiation dose to the patient. Continuous monitoring and early intervention for flap salvage failure is not practicable.

Xenon

Tsuchida [41] described in 1990 blood flow monitoring in 89 patients with deltopectoral flaps, using direct injection of 50 μ Ci xenon-133 into the flap. He distinguished between surviving and non-surviving flaps by the radioactive clearance rate.

Sodium

Harrison et al. [15] described the sodium-22 isotope clearance as a useful technique for monitoring myocutaneous free flaps.

Instrumental monitoring methods

Several instrumental methods for the monitoring of free-tissue transfers have been described.

Hydrogen gas clearance

The technique of hydrogen gas clearance (Aukland [1] in 1964) is based on the same principle as radioactive tracer clearance. It allowed quantitative measurement of tissue blood flow in millilitres per gramme per minute, using an implantable probe in animal models. Glogovac et al. [13] found this technique useful, clinically, in a small number of patients after finger re-plantation. The advantage of implantable probes is that they can be used for monitoring both superficial and buried flaps. Repeated and quantitative measurements of tissue blood flow are possible in different tissue areas at the same time, and the complete monitoring system is available commercially for a relatively low price.

Skin temperature probes

Surface-temperature recording (STR) is one of the oldest and simplest methods of monitoring free flaps. Its usefulness, however, remains poorly documented, and its problems are poorly understood. Skin temperature can be easily and continually monitored with simple, inexpensive equipment [34], and, therefore, much experience has been gathered about temperature monitoring since the 1970s. The blood flow to the skin is related to blood pressure and microcirculation but not in a consistent fashion [40].

It can also be influenced by many factors, including core temperature, ambient air temperature, humidity, light and vasomotor responses. Regional variations of 8°C in the human skin surface temperature were described as early as 1931 [9]. There are generally two types of temperature monitors available, namely infrared thermometry for prognostic assessment of pedicled skin and subcutaneous flaps in animals, and thermoelectric thermometers, as described by Jones [19]. May et al. developed a removable thermocouple probe implanted adjacent to the blood vessel of interest; this invasive technique had promising early results [29]. In a series of eighteen free flaps, two venous thromboses were diagnosed early by this technique. Most measurements today, however, are made with cutaneous thermocouples. They are made of two different metals that produce a small voltage that varies with slight changes in skin temperature. Kaufman's study [21] of muscle flaps suggested that temperature monitoring was not a reliable indicator of flap perfusion unless all environmental influences were monitored and kept absolutely constant so that perfusion was the only variable. Similarly, Issing and Naumann [18] found temperature measurements in their experiments on pedicled skin flaps difficult to measure objectively, due to fluctuations in room

temperature, convection and individual variations in body temperature. In fact, they noted that those flaps that had a more pronounced temperature loss were more likely to remain viable. Lowering tissue temperature by 10°C reduces metabolic demand by 50%; hence, demand for blood flow is similarly reduced. These results supported the observations of Desprez and Kiehn [7], who achieved better survival of pedicled flaps by hypothermia. When properly applied and interpreted, large studies have shown the sensitivity of surface-temperature recording to be 98% and its predictive value to be 75%, making it a simple, inexpensive, and reliable technique of free-flap monitoring [24].

Tissue oxygen tension

Tissue oxygen tension is increasingly recognised as a sensitive and reliable index of tissue perfusion, and preliminary studies suggest that it might be of value in the assessment of free-flap viability. The tissue oxygen tension can be monitored by implantable or surface probes. The pulse oximeter measures the percentage of oxygen saturation of haemoglobin, using two separate wavelengths of light (660 nm and 940 nm) to distinguish between oxygenated and deoxygenated haemoglobin by light absorption differences.

Mahoney and Lista [28] described in 1980 an implantable and disposable tissue oxygen tension monitor. Their initial experience with the technique suggested that a value of less than 20 mmHg was an indication of vascular compromise and the need for careful appraisal of the flap. This technique is simple in its application, disposable and easily placed in the soft tissue of any flap. The sensor also provides digital data that are easy to interpret. However, the technique is invasive, and further clinical work is needed to assess reliability of results. Hirigoven et al. [17] described in 1997 the use of an implantable microcatheter oxygen sensor in a rabbit model. This sensor was sensitive, rapidly responsive and easily interpreted by non-specialist staff. A modification of the licox catheter probe system, used to measure continuously the oxygen partial pressure in body fluids and tissues, has been recently described in this journal. An online alarm system was developed to inform medical staff at the exact moment when the licox software detected a definite fall in the oxygen tension in transplanted tissues. This modification allowed the possibility of immediate surgical intervention and proved successful.

Near-infrared spectroscopy

Near-infrared spectroscopy (NIRS) was described by Thorniley et al. [39] in 1998, and preliminary results show that NIRS was able to detect and distinguish between microcirculatory changes occurring as a result of arterial, venous or total vascular occlusion.

The Erlangen microlightguide spectrophotometer

In 1996, Wolff et al. [45] used a non-invasive Erlangen microlightguide spectrophotometer (EMPHO) to measure blood flow and oxygen supply in free flaps in rats and humans. This technique allowed non-invasive examination of the entire flap surface and permitted a statement on the regional circulation and oxygen supply of individual flap areas. In addition, intra-oral flaps could be easily examined. Unfortunately, this technique cannot be applied to deep flaps, and continuous measurement over several days cannot be made with the EMPHO. Further clinical assessment of NIRS and EMPHO is required.

Doppler flowmeter

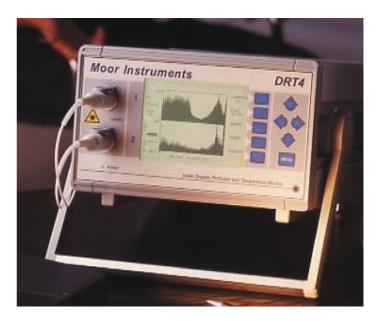
A well-known technique used for adjunctive monitoring of free-tissue transfers post-operatively is the laser Doppler flowmeter (LDF), based on the Doppler shifting of laser light (Fig. 1). This device allows qualitative blood flow measurements to be taken and is commercially available. After a preliminary report on the usefulness of the LDF as a free-flap monitor in 1982, it has become a widely accepted monitoring technique in the USA. Laser Doppler flap monitoring can give warning of flap failures many hours before clinical signs are apparent [20].

Signs of a healthy flap are a pulsatile laser Doppler (LD) blood flow waveform (on "FAST" display mode), due to the cardiac cycle, and a stable or steadily increasing trend. Fluctuations in LD blood flow are also good signs and are due to vasomotor and physiological responses. Signs of a failing flap include lack of pulsatility, a falling trend and lack of fluctuations. Alarm levels should be set relative to baseline flow rather than for "normal" values as, even in the same tissues, there is a wide range of values [16]. Further guidance on the interpretation of laser Doppler recordings have been published elsewhere [37]. LDF is non-invasive and safe, can be used for buried and cutaneous free-tissue transfers, provides continuous recording and can be used to assess anastomotic patency both intra-operatively and post-operatively. Its use is strongly supported by many individuals, and, although the equipment is relatively expensive, it is perceived as being cost-effective [46, 47].

Photoplethysmography

Photoplethysmography utilises a green-light-emitting diode to transmit light into a tissue. Reflected light from haemoglobin in dermal capillary red blood cells is received by a photo-detector and is analysed as light intensity along a frequency spectrum. This method of analysis allows for the removal of "noise" above (stray light and alternating current) and below (room vibrations and respiratory motion) the peak signal (1 Hz to 2 Hz) and results in a means to distinguish between perfused and non-perfused tissues.

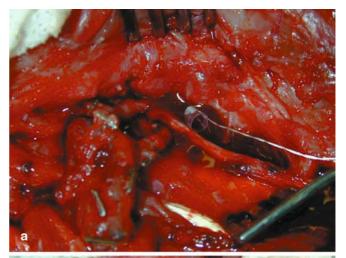
Fig. 1 Laser Doppler flowmeter monitoring system



It has been shown that spectral analysis of photoplethysmograms from radial forearm free-flap (RFFF) patients provides an accurate and rapid means for determining RFFF pedicle vessel patency [35]. Photoplethysmography might provide a clinically useful tool for post-operative perfusion monitoring of free flaps in the future.

Microdialysis

The metabolic activity of free flaps has been monitored by microdialysis, as described by Udesen et al. [42]. Microdialysis is a micro-sampling technique that allows a temporal study of the biochemistry in specific organs or tissues. A double-lumen microdialysis catheter or probe, with a dialysis membrane at the end, is introduced into the specific tissue. Perfusion fluid is slowly pumped through the catheter and equilibrates across the membrane with surrounding extracellular concentrations of low-molecular-weight substances. The dialysate is collected in microvials and analysed. Glucose, glycerol, and lactate concentrations are measured in the flaps and compared with those in a reference catheter that was placed subcutaneously. In a recent study by Udesen, during flap ischaemia the concentration of glucose was reduced, while the lactate and glycerol levels increased. The differences between the flaps and controls were highly statistically significant. After reperfusion of the flaps, the concentrations of glucose, lactate, and glycerol approached normal. With arterial thrombosis, for example, samples from microdialysis showed the concentration of glucose falling to an unmeasurable level; the concentration of lactate increased for a period before it stopped due to lack of glucose and the concentration of glycerol increased to a very high level. This is prob-



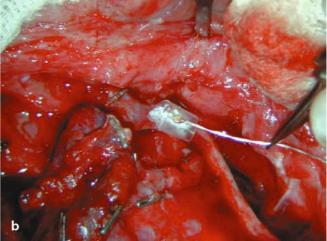


Fig. 2a,b Cook-Swartz venous Doppler system a during positioning and b with probe in situ

ably due to ischaemic damage of the cell membranes, of which glycerol is an important part. Udesen concluded that microdialysis could reliably detect ischemia in free flaps at an early stage, making early surgical intervention possible.

Radiological techniques

A small group of experimental radiological techniques has been described in the literature to monitor free-tissue transfers, using magnetic resonance imaging. Magnetic resonance imaging [11] and nuclear magnetic resonance spectroscopy have been shown to be experimentally useful for examining microsurgical flaps; however, these techniques are too complicated and impracticable for clinical use at present.

Implantable venous Doppler

A promising technique commercially available in the USA is the Cook–Swartz implantable venous Doppler probe, first described by Swartz et al. in 1994 [38]. An implantable 20 MHz ultrasonic probe, properly aligned in a suturable cuff, provides direct vessel monitoring of microvascular anastomoses at a specific site along a designated vessel (Fig. 2). The absence of the monitor's audible signal warns the medical staff that a potential problem with perfusion might exist, thus providing the opportunity for early intervention [25]. A 1 mm piezoelectric crystal placed directly on the vessel provides an effective means of monitoring flow, with improved specificity of vessel origin whilst it is left in situ (3–7 days). When vessel monitoring is completed the probe may be removed by applying minimal traction, leaving only the cuff in situ.

Discussion

Recent advances in technology and improvements in surgical technique have led to reported success rates of free-tissue transfers of between 95 and 98% [23]. Development of a robust method of free-flap monitoring is of critical importance if we are ever to achieve our panacea of 100% success. This ideal monitoring method would reliably detect early flap failure and allow prompt operative intervention to restore flow. Over time, flap salvage rates decline significantly. The ideal time to detect a flap with inflow or outflow compromise is before the patient leaves the operating theatre.

As the speciality of plastic surgery expands, it is increasingly likely for the surgeon to consider free-tissue transfer outside the plastic surgery unit. This will only be possible if reliable monitoring techniques are available. Unfortunately, we cannot assume our medical and nursing staff will always be able to develop the expertise to monitor our flaps effectively.

The best methods of post-operative monitoring available at present are "clinical tests" with adjunctive

techniques such as the laser Doppler flowmeter or the Cook–Swartz implantable venous Doppler probe. We have had good experiences with both these additional techniques. One would be more inclined to use adjunctive techniques in those flaps with traditionally lower success rates, such a non-rectus abdominis flaps and those requiring vein grafts [27]. A body of plastic surgeons is now advocating more "holistic" monitoring, paying special attention to the patient's physiological variables and not just the flap itself.

Core temperature, urine output, oxygen saturation, blood pressure and pulse rate should all be closely monitored and charted in the days following the procedure. Close involvement of the anaesthetic staff in the post-operative period would be beneficial.

Some of the additional techniques we describe, although not in routine use at present, may be logistically feasible to allow post-operative care to be optimised in the future.

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