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The use of sentinel skin islands for monitoring buried and semi-buried micro-vascular flaps. Part I: Summary and brief description of monitoring methods

Martin Molitor[a], Ondrej Mestak[a], Richard Pink[b], René Foltán[c], Andrej Sukop[d], Stefano Lucchina[e]

Micro-vascular flaps have been used for the repair of challenging defects for over 45 years. The risk of failure is reported to be around 5-10% which despite medical and technical advances in recent years remains essentially unchanged. Precise, continuous, sensitive and specific monitoring together with prompt notification of vascular compromise is crucial for the success of the procedure. In this review, we provide a classification and brief description of the reported methods for monitoring the micro-vascular flap and a summary of the benefits over direct visual monitoring. Over 40 different monitoring techniques have been reported but their comparative merits are not always obvious. One looks for early detection of a flap's compromise, improved flap salvage rate and a minimal false-positive or false-negative rate. The cost-effectiveness of any method should also be considered.
Direct visualisation of the flap is the method most generally used and still seems to be the simplest, cheapest and most reliable method for flap monitoring. Considering the alternatives, only implantable Doppler ultrasound probes, near infrared spectroscopy and laser Doppler flowmetry have shown any evidence of improved flap salvage rates over direct visual monitoring.

Key words: micro-vascular flap, free flap, monitoring methods, sentinel skin paddle, monitoring skin island, buried flap, semi-buried flap

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[a]*Department of Plastic Surgery, First Faculty of Medicine Charles University and Na Bulovce Hospital, Prague, Czech Republic*
[b]*Department of Maxillofacial Surgery, University Hospital Olomouc and Faculty of Medicine and Dentistry, Palacky University Olomouc, Czech Republic*
[c]*Department of Maxillofacial Surgery, General University Hospital and 1st Faculty of Medicine, Charles University, Prague, Czech Republic*
[d]*Department of Plastic Surgery, University Hospital Kralovske Vinohrady and 3rd Faculty of Medicine, Charles University, Prague, Czech Republic*
[e]*Hand Unit, General Surgery Department, Locarno's Regional Hospital, Via Ospedale 1, 6600 Locarno, Switzerland*
Corresponding author: Martin Molitor, e-mail: martinmolitor1@gmail.com

INTRODUCTION

The transfer of micro-vascular flaps (MF) in reconstructive surgery is a reliable and well-established method for repairing defects of various aetiology, size and depth. Surgery involving MF however, can be challenging which is sometimes made more so when reliable monitoring is difficult to achieve. The risk of failure of MF is reported to be around 5-10% (ref.[1,2]) and despite developments in techniques, instruments, sutures and devices during the last decades, it remains unchanged[3]. Loss of the flap is still the most significant risk for a patient with the associated consequences; the need for remedial/replacement surgery, additional morbidity of another donor site and prolonging treatment time. From the point of view of the healthcare provider, the increased financial burden is also of prime importance.

The principal complication leading to flap failure is vascular in origin. The patency of micro-vascular anastomoses is crucial for flap viability. When a problem occurs, it is often within the first 48 h post-surgery. Vascular compromise requiring re-exploration is reported as occurring in 12-17% of cases[4,5]. Timely detection of a flap vascular problem is very important as about 70-80% of flaps can be rescued by remedial surgery if done in time[6]. The success of remedial surgery is inversely proportional to the period between the recognition of the complication and the commencement of remedial surgery. Kerrigan et al. in 1984 reported that the tolerated ischemia time of a MF after vascular occlusion is about half of that during primary flap transfer[7]. Logically, earlier detection leads to higher success rates of salvage procedures. It was found that after 1 to 4 h of ischemia, 100% of flaps can be salvaged, after 8 hours the success rate decreases to 80% and after 12 h all flaps fail[4,5,8].

Reliable monitoring of the MF blood flow is therefore crucial for early detection of vascular failure leading to prompt revision surgery with a high rate of flap salvage. During the era of micro-vascular reconstructive surgery, about the last 45 years, the first and most widely used method of flap evaluation was (and still is) direct visual monitoring (DVM).

Though clearly monitoring is of utmost importance, a survey of units performing MF surgery shows considerable differences in the monitoring methods selected. Currently there is no established or generally accepted standard, algorithm or approach for monitoring the MF. Microsurgical units usually implement DVM with or without some other method, predominantly Doppler ultrasound (DUS) or laser Doppler flowmetry (LDF) (ref.[9-11]).

Usually flaps are visible and accessible for DVM. But in maxillofacial surgery, digestive tract reconstruction, vascularised lymph node transfer, long bone restoration and breast or vaginal reconstruction, flaps can be completely buried and DVM is not possible. Flaps used for upper digestive tract reconstruction are "semi-buried"; they are accessible for direct visualisation but with difficulties and their surface is often difficult to evaluate due to saliva maceration[12]. In buried or semi-buried flaps, methods other than DVM must be considered. Another variation that allows DVM in some instances however, is the incorporation of a skin island[13-16].

A plethora of monitoring techniques have been reported however it is difficult to extract data to find the comparative benefit of particular technique. We suggest the following criteria need to be assessed for informed comparison; (a) salvage rate - that is the ability of a monitoring method to allow early intervention and salvage of a truly compromised flap, (b) false-positive rate - that is the proportion of false positive readings leading to needless re-explorative surgery where the flap was not actually compromised, (c) false-negative rate - which is the proportion of false negative readings that result in flap loss, (d) patient's perception of the monitoring process, and (e) cost-effectiveness. Considering the benefit of more sophisticated methods over DVM we believe, that several issues need to be considered; (a) its reliability and validity, (b) its economic benefit and (c) patient perception and tolerance.

These pieces of information are generally missing or poorly considered in the majority of published works[3,17].

In this review we have compiled and grouped all reported monitoring methods published to date. We have then classified these methods according to their complexity and then detailed methods that are required to be used where DVM is not possible or efficacious. Also we provide an overview of currently reported monitoring methods and their claimed benefits over DVM after our consideration.

MATERIALS AND METHODS

We carried out a literature search for the period from 1975–2019 using the bibliography of the database PubMed. Search terms included; free flap monitoring (652 articles), micro-vascular flap monitoring (246 articles), microsurgical flap monitoring (117 articles) and free tissue transfer monitoring (285 articles) totalling 1.300 articles. From this set we excluded (a) duplicate references, (b) references where flap monitoring was peripheral to the topic and (c) invalid or irrelevant references. This left us with 356 valid articles on which to base this review.

As some methods (e.g. Doppler ultrasound and Laser Doppler flowmetry) are used quite routinely and were therefore reported many times in the 356 valid articles we only cited 185 of these in our reference list, selected on the principle that they brought new relevant information to the discussion.

METHODS OF MONITORING THE MICRO-VASCULAR FLAP

More than 40 methods to monitor flap vascularisation have been reported over the 45-year period of routine MF surgery. The surgeon's intention in every case was to provide a method that would objectively, rapidly and easily provide warning of a compromise event to increase the chance of saving the problematic flap.

There have been many criteria used for classification of monitoring methods. Moubayed[18] for example made two classes namely; (a) widely used – DVM and Doppler, near-infrared spectroscopy and (b) experimental – all other methods. Schoeller[19] chose objectivity of the method as the criteria and concluded that his two classes were; (a) subjective – DVM and (b) objective – all the other methods. It is however disputable which methods are truly objective, as some degree of subjective evaluation is often needed in reading and interpreting the findings. In this review we classify monitoring methods according to their complexity as depicted in Table 1.

Direct visual monitoring

Is subjective yet generally and routinely used and a very reliable method[20-26]. However this is only the case when the flap's surface is at least partially exposed but this is not always true. DVM has the advantage of being the cheapest, simplest and most convenient method of all and can be done by any trained staff (medical, nursing or supportive). It also does not require any special technical additions such as medications, services, facilities or devices.

Non-invasive device-dependent methods

These encompass a wide variety of methods that use special probes, sensors, cameras, transmitters, microscopes, tomographs and the like. Some of them were reported to have better monitoring capacity than DVM (ref.[20,27-30]). However, like DVM they also need the direct access to the flap's surface and are not suitable for buried or semi-buried flap monitoring. They are more demanding of special materials, medications, facilities, devices and often specialised personnel.

Invasive device-dependent methods

Use implantable equipment that can be placed next to a flap's tissue or pedicle and are therefore able to monitor buried or semi-buried flaps. These methods often

Table 1. Classification of micro-vascular flap monitoring methods.

Complexity	Method
Device free	Direct visual monitoring Bromphenol blue
Non-invasive device-dependent	Surface skin temperature (touch or no-touch) Doppler ultrasound (handheld) Pinprick glucose testing Power Doppler Tissue harmonic imagingtrade mark Speckle reduction imagingtrade mark Laser Doppler flowmetry Oxygen to See Confocal laser scanning microscopy Laser speckle contrast imaging Visible light spectroscopy Microlightguide spectrophotometry Diffuse correlation spectroscopy Diffuse reflectance spectroscopy Diffuse correlation spectroscopy/transcutaneous pulse oximetry Near infrared spectroscopy Pulse oximetry Multispectural spatial frequency domain imaging Luminiscence ratiometric oxygen imaging Photoplethysmography Impedance plethysmography Peroral fluorimetry Orthogonal polarised light Compound muscle action potentials Side-stream dark field imaging Hydrogen clearance Contractility/electromyographic activity
Invasive device-dependent	Implantable Doppler probes Contrast enhanced Doppler Electromagnetic flowmetry Implantable spectroscopy probes Implantable probe pulse oximetry Intraparenchymatous venous pressure monitoring Invasive temperature monitoring Tissue oxygen tension monitoring Impedance plethysmography Intravenous fluorimetry
Vascular network and blood flow visualisation	Classic contrast angiography Indocyanine-green fluorescence video angiography Computed tomography angiography Magnetic resonance imaging angiography
Nuclear	Scintigraphy Positron emission tomography Radioactive microspheres Xenon washout method
Laboratory	Micro-dialysis Continuous pH monitoring
Technical supportive	Digital photography sharing by Internet Smartphone applications

utilise the same principles as non-invasive device dependent methods and can sometimes have better sensitivity than DVM, especially in cases of buried and semi-buried flaps[29,31]. They also require special materials, medications, facilities, devices and specialised staff.

Vascular network and blood flow visualisation

These are precise methods but are demanding for the patient, the medical staff and require special equipment and facilities. They generally require the transport of the patient to and from a specialised unit. They are suitable for the monitoring of buried and semi-buried flaps, however due to practicality issues they are used very sparingly. They are not suitable for continuous monitoring of MFs (ref.[3]).

Nuclear methods

These present the same advantages and disadvantage as vascular network visualisations and are used even more exceptionally. The superiority of these methods over blood flow visualisation is that they are able to confirm not only blood flow inside the vessels, but also the viability of the flap's tissues[32,33].

Laboratory methods

These are complex and evaluate the metabolic changes inside the MF tissues. Though they can be used in all kinds of flaps, they are not utilised routinely as their benefit over other methods is not yet confirmed and are very challenging regarding results interpretation[34-37].

Technical supportive methods

These do not introduce any new or inventive methods. They just utilise the Internet and a smartphone with a camera to monitor free flaps remotely using other monitoring methods[38-40].

In general for monitoring of exposed flaps we can use and more-or-less rely on any of the previously mentioned methods. However this is not the case for buried and semi-buried flaps. A summary of the limitations of the monitoring methods is presented in Table 2.

Table 2 specifies the limitations of monitoring methods with respect to the possibility of replacing DVM in the case of buried or semi-buried flaps. Some methods still require access to or even contact with the flap surface. In some methods the penetration of the monitoring stream is limited in depth. Several methods are specific for some kinds of tissue and are therefore not suitable to monitor all flaps but only flaps containing this specific tissue.

BRIEF DESCRIPTION OF MONITORING METHODS

Direct visual monitoring is subjective and observer dependent but it remains the prevalent method due to its simplicity, cost effectiveness and reliability[20-26]. It has the disadvantage that it requires some degree of experience and there is an initial learning curve for the observer to recognise subtle flap alterations. Naturally this method requires the flap to be entirely or partially exposed. In the case of semi-buried flaps used for upper digestive tract reconstruction, DVM may be possible directly or with the aid of endoscopic or micro-endoscopic techniques[12].

DVM encompasses a range of tests and observations of colour, surface temperature, turgor/elasticity/consistence, capillary return/refill, blanching time, pinprick / needle stick testing or bleeding after scarification. These characteristics are of course variable and change during the recovery stages. Most microsurgeons would agree that there is no current alternative that entirely supplants DVM. This is because an overall assessment of the flap condition involves consideration of multiple clinical indicators[3].

Some of the specifics of DVM need to be described in more details.

The colour of flap should be similar to the general skin colour of patient. However, often there is some degree of skin hyperaemia as a reaction to the flap's ischemia time immediately after surgery. We also have to consider that the colour of the recipient region may be somewhat different from that of the donor flap site. Paleness usually indicates ischemia of the flap and a bluish colour may indicate venous congestion[26]. Where a patient is naturally pale skinned, we can enhance skin colour and capillary refill evaluation by inducing a histamine skin reaction. A gentle scarification/irritation of skin causes histaminergic activation by histamine released from skin mast cells. This results in local angioedema characterised by a wheal and flare. The irritated region becomes pinkish/reddish and blanching time is more easily evaluated[115]. However for patients with dark skin, evaluation of the flap skin colour can be difficult or impossible. While it may be true that some skin colour changes occur suddenly, it is often an insidious process that can take 1-2 h to determine. It has been suggested that colour digital photography immediately post-surgery could provide a baseline from which to measure change[26,116].

The flap turgor should be elastic and soft to the touch. Poor turgor of the flap suggests ischemia while dark oedema indicates venostasis. The elasticity is evaluated by touching and compressing the flap's surface which is a very subjective process. While there are devices available for more objective measurement of skin elasticity (cutometers) we did not find any reference to their use in these procedures.

The flap temperature should be similar to that of the surrounding tissue. It is estimated simply by touching the surface of flap and a control region. This again is very subjective. The flap's surface being relatively cold can indicate ischemia as well as venous congestion. The clinical usefulness of temperature assessment is questionable due to its variability and influence by many external factors[26]. It has also been noted that when the temperature falls significantly, vascular damage is usually irreversible in any case[117].

Capillary refill time/blanching time is measured by applying gentle pressure usually using some device – spatula or similar for three seconds. A refill time of 3-5 s is considered normal. No blanching or a very slow refill indicates ischemia while a very quick refill suggests venostasis[118-120]. The pressure applied should be gentle to prevent bruising but even when it has occurred, flap survival rate was not affected[26,121].

The pinprick/needle stick test should not be used routinely as it damages the flap's surface and presents perforation risks even to the point of vascular pedicle damage. This test always causes generalised bruising and mild scaring of the flap's surface. It is usually reserved as a last resort if there is high uncertainty with other clinical findings. Where it is found there is no or very postponed bleeding on testing it suggests an arterial problem. If there is a rapid exit of dark blood, this indicates a venous compromise[118].

It has been noted when regular DVM was carried out during the first few postoperative days, some units were reporting flap salvage rates of up to 80% and overall success rates of up to 99% (ref.[17,122-128]). Though many stud-

Table 2. Limitations of methods for monitoring the buried flaps.

Limitation	Method	Ref.
Need for surface exposure or contact	Direct visual monitoring	20-26
	Bromphenol blue	1,41
	Pinprick glucose testing	42
	Surface temperature	43-45
	Handheld Doppler ultrasound	46-48
	Power Doppler	49-51
	Contrast enhanced Doppler	49,52,53
	Oxygen to see	54,55
	Laser speckle contrast imaging	56
	Confocal laser scanning microscopy	57
	Surface pulse oximetry	58-61
	Microlightguide spectrophotometry	54,62
	Surface diffuse correlation spectroscopy	63
	Surface diffuse reflectance spectroscopy	63
	Multispectral spatial frequency domain	64-66
	Luminiscence ratiometric oxygen imaging	67,68
	Photoplethysmography	69,70
	Fluorimetry	71-75
	Orthogonal polarised light	76-78
	Technical supportive methods	38-40
	Radioactive microspheres	79,80
	Xenon washout method	81,82
	Side-stream dark field imaging	83,84
Limited depth of penetration	Laser Doppler flowmetry (8 mm)	85-88
	Tissue harmonic imagingtrade mark (3 cm)	49-51
	Speckle reduction imagingtrade mark (3 cm)	49-51
	Visible light spectroscopy (8 mm)	20,89,90
	Near infrared spectroscopy (10 mm)	91-95
Only skin	Luminiscence ratiometric oxygen imaging	67,68
Only muscle-containing flaps	Compound muscle action potentials	96
	Contractility/electromyographic activity	97
Only muscle and vascularised bone	Tissue oxygen tension	58,59
Not dark skin and not muscle	Fluorimetry	71-74,98,99
Universal not limited	Probe Doppler ultrasound	100,101
	Electromagnetic flowmetry	102,103
	Probe pulse oximetry	58-61
	Probe diffuse correlation spectroscopy	63
	Probe diffuse reflectance spectroscopy	63
	Intraparenchymatous venous pressure monitoring	104
	Invasive temperature monitoring	105
	Impedance plethysmography	106
	Hydrogen clearance	109,110
	Classic angiography	3
	Indocyanine-green fluorescence video angiography	3,75
	CT angiography	3
	MRI angiography	3
	Scintigraphy	33
	PET using oxygen-15 labelled water	32,111
	Micro-dialysis	34,35,112,113
	pH monitoring	36,37,114

ies report the superiority of DVM over other methods, statistically valid clinical trials scientifically confirming its benefits are still absent[129]. However, as DVM is used by all microsurgical units, it is suggested that it should be therefore accepted as the standard against which other methods are compared[17,130,131].

Skin surface temperature (SST) as a monitor was first reported in 1981 by simply using a thermometer[41,43-45]. This elementary method is not in routine use however, as it was shown, that SST changes were only significant after 15 hours of flap ischemia and that is far too long for successful flap salvage[117,72]. Novel, more sensitive methods to detect radiation in the infrared range of the electromagnetic spectrum using no-contact techniques were developed[53,132]. A difference of more than 1.8 °C between the control and the flap skin was defined as an indicator of an ischemic event. Another retrospective analysis concluded that a decrease greater than 3°C is a significant indicator of arterial thrombosis while reduction 1-2 °C may indicate venous occlusion[133]. Authors concluded the main problem with SST monitoring is that it can fluctuate by as much as 8 °C depending on clothing, humidity, core temperature, room environment and other variables.

Invasive tissue temperature monitoring utilises two implantable thermocouple probes: distally and proximally from the arterial anastomosis. When arterial or venous thrombosis occurs, reduced blood flow leads to decreased temperature recorded by distal probe. A temperature difference between the probes of more than 0.3 °C has been advocated as indication for re-explorative surgery[105,106].

Bromophenol blue is a dye that is injected intravenously and the observer assesses the visible distribution of the dye in the monitored tissue. Should the flap tissue not show the passage of dye it signals arterial obstruction whereas prolonged dye elimination indicates venous compromise. The recommended interval between examinations is 6 h. However the presence of residual dye may confuse interpretation and further, a 6 h interval is considered too long to provide notice for effective re-explorative surgery[1,41].

Pinprick glucose testing was suggested as an adjunct to DVM (ref.[42]). The authors measured glucose levels with a standard commercial blood glucose monitor used by diabetics and compared the levels found in congested flaps with that of a nearby control area. The study consisted of four MF and two pedicled flaps in total. They found a significantly lower level of glucose in the congested flaps relative to the control areas and postulated that vein occlusion caused pooling of glucose-depleted blood in the tissue.

Doppler ultrasound effect of blood flow in the flap pedicle can be followed indirectly over the skin (surface monitoring using low-frequency continuous-wave ultrasound or colour DUS) or directly with a probe implanted perivascularly (Swartz or Cook system) using a cable or wireless[46,47,101,134-138]. Conventional DUS methods are sensitive for the diagnosis of arterial thromboses, however with venous thromboses, the positive arterial signal can persist for several hours after a venous thrombosis occurs. To remedy this it is suggested the probe is placed on a vein. A greater sensitivity is reported compared with probes used for monitoring arterial flow. A venous Doppler signal instantly detects both venous and arterial flow compromise. A complication arises when monitoring an area with a rich vascular network as it is difficult to be certain that Doppler probe does not provide false positive signals from vessels other than that of the flap's pedicle. This is a more pronounced problem for a handheld probe where it is also difficult to distinguish between an arterial and venous signal. Several comparative studies and meta-analyses demonstrated an increase in the flap salvage rate compared to DVM (88% vs. 66%) (ref.[8,27-31]). In the case of buried flaps, clearly an implanted DUS probe facilitates a much better salvage rate than DVM (94% vs. 40%) (ref.[29]). The implantable Doppler probes are associated with a small risk of false positives and probe malfunction. This is likely to be due to a learning curve for the surgeons in placing the probe and all medical staff in reading and interpreting the signal[100,101,135]. The DUS seems to be one of the most promising among all techniques other than DVM, especially in buried and semi-buried flaps[134].

Contrast enhanced ultrasound uses a special ultrasound contrasting agent containing sulfur hexafluoride and has 100% sensitivity and 86-100% specificity in predicting flap failure[49,52,53]. The imaging method of contrast-enhanced ultrasound uses the non-linear harmonic parts of the ultrasound waves caused by the contrast agent to provide more resolution. However repeated exposure to intra-venously administered contrast media and the potentially long period between suspicion and examination are the main downfalls of this method.

Another refined ultrasound techniques such as *colour coded DUS, cross beamtrade mark and ultrasound computer tomography technique in B-scan* have been reported[49-51,139]. *Power Doppler* is able to detect and assess anastomotic vessels even if they are elongated or twisted. The method is sensitive to low blood flow but is unable to detect flow direction. *Tissue harmonic imagingtrade mark* offers better contrast and spatial resolution by using the non-linear harmonic portion of ultrasound waves caused by monitored tissue, while *speckle reduction imagingtrade mark* reduces the grey scale artefacts[139]. Cross beamtrade mark with tissue harmonic imagingtrade mark and speckle reduction imagingtrade mark were used to investigate the peripheral parts of the flaps. These methods were also able to assess the patency of anastomosed vessels and allowed dynamic blood flow monitoring at the microcirculation level to the depth of up to 3 cm[49-51]. However, only very few studies with a limited number of MF cases were used to evaluate these new methods so further validation is needed to prove reported conclusions.

Laser Doppler flowmetry is used to assess capillary blood flow inside the flaps. The doppler shift of a laser shone into a tissue is used to calculate the speed at which the blood is flowing. The trend of measured perfusion is important rather than the absolute value, especially in case of venous occlusion. A 100% successful detection rate of vascular compromise was reported[85-88,140,141-145]. LDF can reveal a MF compromise several hours before the onset of visual signs. False-positive/negative rates are very low[46,47,88]. LDF poses many characteristics of an ideal monitoring device as it is non-invasive, sensitive, instantaneous and provides continuous data about perfusion[20]. Few studies declared similar salvage rates to DVM alone but one study reported increased salvage rate from 50% to 85% (ref.[145]). This study was however done on 12 problematic MF cases only[85]. The major limitation of LDF is the depth of penetration (8 mm maximum) that restricts its use in monitoring buried flaps.

Electromagnetic flowmetry permits monitoring of pedicle blood flow. The probe producing an electromagnetic field is placed next to pedicle and measures the electrical potential generated by a column of blood passing through the magnetic field. The intensity of electromagnetic potential is linearly proportional to the intensity of blood flow. A decrease of potential indicates vascular obstruction[1,102,103].

Oxygen to See utilises the LDF in combination with white light spectrophotometry[54]. The main advantage over simple LDF is that it enables dependable differentiation between venous and arterial occlusion[55,147]. Considerable operator experience is required for reliable interpretation of findings as it's sensitivity is not sufficient to detect low but acceptable perfusion rates early post-operatively and can be incorrectly interpreted to indicate vascular compromise[55,146]. However once flow is established, a downward trend after the second postoperative day indicates the need for re-exploration.

Laser speckle contrast imaging is a camera-based technique that illuminates an area of tissue with divergent 785 nm light and analyses the interference pattern of the light that is scattered from the tissue. The method is more sensitive than LDF when detecting venous obstruction. However, it requires contact with the MF surface, is very sensitive to motion artefacts and is expensive[56].

Confocal laser scanning microscopy allows non-invasive, real-time evaluation of tissue microcirculation with a high cellular resolution at the capillary beds of free flaps. The method allows quantitative measurement of blood-cell flow, diameter of the capillary loops and thickness of the epidermis. Venous congestion is characterised by a decrease in blood-cell flow of up to 41%, increasing of the capillary loops diameter up to 22% and increasing of the epidermis thickness up to 32% due to oedema and vascular dilatation. By contrast, arterial occlusion is defined by a decrease in blood flow of up to 90% accompanied by insignificant change of both capillary loop size and epidermal thickness[57].

Visible light spectroscopy (VLS) uses visible light in real time to measure the haemoglobin saturation at capillary level. Visible light is absorbed by haemoglobin approximately 100 times more than infrared light therefore this technique theoretically should be more sensitive than methods using infrared light. VLS can detect flap ischemia earlier than DVM and an implantable DUS probe but the authors did not report the impact on flap salvage rate[89,90]. The disadvantage of tissue VLS is that it is designed to measure at the depth of cutaneous capillary beds, therefore the readings are non-specific and can reflect both flap vascular compromise as well as systemic problems like desaturation or hypotension. In its favour, VLS is non-invasive, sensitive, immediate and provides continuous data about flap perfusion so it has potential as an ideal monitoring method[20]. It is however expensive and with a maximum depth of penetration of 8 mm it limits its use in monitoring buried flaps.

Microlightguide spectrophotometry is a non-invasive method that uses white light from a xenon lamp. Differences between levels of oxyhaemoglobin and deoxyhaemoglobin are measured. Vascular occlusion, both arterial and venous, leads to immediate and massive decreases in haemoglobin oxygenation with increasing of deoxyhaemoglobin values[54,61].

Diffuse correlation spectroscopy enables the quantification of relative changes in microvascular blood flow. It uses coherent near-infrared light to penetrate tissue while the detector monitors speckle fluctuations in the scattered diffuse light. The speckle signal is modulated by the overall motion of all things that cause scattering in the tissue. The signal modulated by blood cells (predominantly erythrocytes) dominates the spectrum. The probes can be superficial or implantable[63].

Diffuse reflectance spectroscopy uses a broadband light source to measure tissue vascular oxygenation. Oxygen saturation of blood is calculated as a result of obtaining quantitative values of oxyhaemoglobin, deoxyhaemoglobin and total haemoglobin concentrations using the tissue absorption coefficient. Both diffuse correlation and diffuse reflectance methods provide a portable, non-invasive and inexpensive alternative for microvascular blood flow measurement. Early warning of flap failure was reported[63].

Multimodal diffuse correlation spectroscopy combined with diffuse reflectance spectroscopy system has been constructed and tested. The measurements were done on the artery, muscle and skin of the MF in a porcine model but only on two animals. A significant inconsistency in obtained measurements was noted and the authors concluded that further development work is needed[148,149].

Near infrared spectroscopy (NIS) is non-invasive method that measures tissue oxygen saturation and total haemoglobin index using a special probe. It can be used in buried flaps if the overlying tissue is less than 10 mm thick. The method provides continuous and dynamic monitoring of flaps and is able to distinguish between arterial and venous occlusion which is an advantage over classic pulse oximetry. It is not affected by extrinsic factors, such as blood pressure, perforator size and number etc[91]. The changes in oxygen saturation and total haemoglobin index can precede visual manifestation so near NIS can detect vascular compromise earlier that DVM or even DUS (handheld or implantable probes) (ref.[91-95]). Two out of three comparative studies reported statistically significant better flap salvage rates when using NIS together with DVM than when using DVM alone[93,94,100,150].

Pulse oximetry (PO) estimates real-time oxygen saturation of arterial haemoglobin and follows the difference between decreasing O2 pressure and increasing CO2 pressure[151,152]. In detecting flap ischemia the levels of O2 seem to be more sensitive than CO2, in venous congestion it is vice versa[153,154]. O2 level reacts immediately to changes in microcirculation and can appear several hours earlier than the visual symptoms[30,155]. PO can be utilised transcutaneously or using implantable or transflectance probes[58-61]. Although there are anecdotal reports using PO as a monitoring method, to date there is no valid study to demonstrate PO as having any advantage over DVM (ref.[17]).

Multispectral spatial frequency domain imaging is an oxygenation-imaging technique that permits monitoring of tissue oxygenation over a large area. It detects a decrease in oxygen saturation (a result of blood flow obstruction) earlier than visual signs. So far only a limited number of studies have been carried out and mainly in animal models[64-66].

Luminiscence ratiometric oxygen imaging measures the relative transdermal oxygen consumption between the flap and well perfused normal skin. The operating assumption is that transdermal oxygen consumption of a well-perfused flap should be lower than that of a poorly perfused flap. The method uses a fluorescent oxygen sensory foil with an oxygen reservoir that covers the skin surface of the flap and a handheld fluorescence microscope. It was concluded that a relative consumption of less than 0.3 indicates good flap condition[67]. However this method requires contact with the skin surface and is able to only evaluate the skin condition but not the deeper tissues[68].

Fluorimetry was used in the 1940s to predict the survival of suspect areas of pedicled flaps and it was found to be accurate. It measures the ultraviolet-induced fluorescence in tissue following intravenous injection of fluorescein dye and renal excretion that represents arterial and venous phases respectively[156]. Introduction of fiberoptic fluorimetry allowed for the monitoring of both perfusion and elimination phases simultaneously, the use of small portion of dye but requests frequent examinations[157,73,74]. Subsequently other studies demonstrated that it is possible to use oral introduction of fluorescein or indocyanine green[72,158,159]. Studies demonstrated this technique to significantly increase the flap salvage rate in comparison with DVM and to be a more specific indicator of flap survival than pH or SST monitoring[71,72,75]. However the technique has significant disadvantages, namely; a possible allergic reaction to the dye, nursing time demands and inefficacy with dark skin and muscle tissue.

Orthogonal polarised light is relatively new method with no clinical studies performed to date. The technique uses polarised light to determine the microcirculation inside the skin. A special probe emits polarised green light of 548 nm towards the skin and a certain portion is reflected back. A second polariser filters the reflected light so that only light that has undergone a polarity change due to its interference with haemoglobin caused by Rayleigh scattering can be visualised. Animal studies proved this technique to be accurate in predicting flap necrosis. The use of this method for monitoring of the MF in a clinical setting has been proposed[76-78].

Compound muscle action potentials can be used to estimate the amplitude, latency, and duration in muscle flaps to assess muscle functional capacity that decreases in the case of ischemia caused by vascular obstruction. The critical values of amplitude changes for vascular compromise are more than 40% initially and continue decrease thereafter[96].

Contractility or electromyography (EMG) in response to electrical stimulation was used as an index of muscle viability, i.e., intact circulation. However, contractions as well as EMG potentials could be evoked 1-4 h after blood flow had been arrested. Spontaneous EMG activity, which can be recorded 2-3 weeks after denervation, is affected earlier than muscle excitability; thus, the recording of spontaneous EMG activity may serve as better electrophysiological method for post-operative monitoring of vascularisation in free muscle transfers[97].

Photoplethysmography (PPG) shines bright light into tissue using a green or infrared light emitting diode. Reflected light from haemoglobin in the dermal capillary red blood cells is detected and analysed as light intensity along a frequency spectrum. PPG directly measures the intensity of reflected light from red blood cells at their reflective wavelength characteristic. This method seems to be able to distinguish between perfused and non-perfused tissues with high sensitivity, specificity and a positive predictive value. The technique is claimed to be much more accurate than LDF as it demonstrates higher correlations to radioactive microsphere results. PPG can be upgraded by using a hand-held computer[69,70].

Impedance plethysmography uses a small electrode array in which an alternating electric current is passed through a buried free flap. Induced voltage across a small volume is measured. A graphical display of this changing voltage illustrates the pulsatile flow through the flap, enabling continuous assessment of perfusion. The method should be accurate, easily interpreted and therefore suitable for inexperienced staff. It is also able to reveal pedicle obstruction very quickly and to distinguish between arterial and venous blockages[107,108]. The technique is however invasive and no detailed comparative studies have so far been conducted.

Intra parenchymatous venous pressure monitoring uses a special catheter. Change of venous pressure corresponds to arterial or venous thrombosis either by decreasing or increasing respectively. The sensitivity rate was reported to be 86%; specificity rate 96%; positive predictive value rates 64%; negative predictive value rate 99% and false positive rate 4%. The flap salvage-rate was 83% in venous thrombosis and 33% in arterial thrombosis cases[104].

Tissue oxygen tension measures the pressure gradient between oxygen delivered to the tissue and its actual consumption by mitochondria. This technique presents a sensitive method for detecting circulatory impairment in muscle and bone transfer but is not very reliable for skin bearing or composite flaps[58,59].

Side-stream dark field imaging is non-invasive method being tested in animal models but rarely in clinical practise yet. It was proposed as a useful monitor in patients with pigmented skin where clinical examination is difficult to assess accurately. The method evaluates end-capillary microcirculation at cellular level using a central light guide that is surrounded by concentrically placed stroboscopic light-emitting diodes to procure side-stream dark field illumination. Real time visualisation of red blood cells and all other cells present in the blood stream is provided. The significant advantage is that this method requires minimal training and it presents a direct measure of blood flow[83,84].

Hydrogen clearance estimates impedance changes of the tissue because of H_2 concentration variations within it. The changes in H_2 concentration are registered by electrodes and mathematical analysis of clearance enable quantitative expression of blood flow values in millilitres/minute/100g of tissue. Limited reports suggest that the method is reliable, simple and is able to detect changes in blood flow earlier than DVM. Also it is possible to distinguish between arterial and venous compromise[109,110].

Classic angiography, intravenous indocyanine-green fluorescence video angiography, computed tomography (CT) angiography or magnetic resonance imaging (MRI) angiography are methods, which directly visualise anastomoses patency and the vascular network of tissues. These methods are very specific and while providing unique information they are more suited to the research world rather than routine clinical practice due to cost, specialist facilities and staff needed to run them versus the timeliness of the information they can provide[3,124]. These methods also require the application of various contrast agents which present an added risk of allergic reactions and some of them expose the patient to a considerable radiation load. They are certainly not convenient for continuous monitoring[3,75].

Scintigraphy (SG) and Positron emitting tomography (PET) are methods that evaluate special radioactive markers inside tissues after intravascular introduction. Should a vascular pedicle of the flap be compromised, the concentration of markers in the flap tissue is reduced or absent[15,32,33,111]. Isotope techniques are able to show whole flap perfusion and its quantification so they can detect the areas of hypo-perfusion. For SG several isotopes have been studied such as 85Kr, 22Na, 133Xe and 99mTc (ref.[33,78,160,161]). PET uses radio-labelled glucose to quantify the metabolic state of tissue or oxygen-15 labelled water to quantify blood flow. Nuclear methods have the same practical disadvantages as mentioned for angiographies, in addition the technique requires a reasonable amount of time between the injection of the radioactive agent and the detection of the isotope inside the tissue. PET however has been considered useful for flap condition assessment in a late postoperative setting[162].

Radioactive microspheres have been used in an experimental setting to study flap circulation. Intravascular injection of radioactive microspheres leads to their entrapment in tissue to an extent that is proportional to its arterial blood supply. The measured intensity of radiation allows the quantitative approximation of arterial blood supply to be calculated. The method is however not suitable for clinical use as the tissue must be sacrificed and undergo sectioning to carry out the measurement[79,80].

Xenon washout method uses radio-labelled xenon that is injected intra-dermal. Computer modelling of the decreasing signal as the xenon dissipates from the site provides an indirect determination of blood flow. The method requires manipulation with radioactive material, a sophisticated computing system and is difficult to perform at a patient bedside[1,81,82].

Laboratory methods offer continuous monitoring of the metabolism in tissue by observing levels of glucose, glycerol, lactate, pyruvate and the lactate/pyruvate ratio, usually using micro-dialysis (MD) provided by a subcutaneously placed double-lumen catheter with a semipermeable membrane. This method detects the metabolic changes following cell damage caused by ischemia. A typical finding is very low glucose concentration, a high lactate/pyruvate ratio and elevation of the lactate concentration[35,163]. Other molecules like complement component 3 (C3) and thromboxane A2 have also been studied[164,165]. MD and *rapid sample MD* can be useful in cases involving buried flaps and should be able to provide an accurate and objective measure of MF metabolism. By recognising changes in ischemic tissue it should be able to produce early and sensitive warning of flap failure[34,35,112]. The method was tested on a rectus abdominis flap and was reported to be so sensitive that it is able to determine the difference in metabolism between micro-vascular and pedicled flaps and even between zones I and II of pedicled flaps[166]. MD indicates vascular compromise significantly earlier than visual signs (5 to 7 h earlier) with higher specificity but this has been demonstrated on 20 flaps only[167]. A glucose level of less than 3.85 nmol/L and lactate levels greater than 6.4 mmol/L indicate pedicle compromise with 98.5% sensitivity and 99.5% specificity. Frost reported a superior detection rate in comparison with DVM and DUS and a zero false positive rate[31]. However another study found no benefit of MD over DVM and to the contrary, they found a higher false-positive rate[131]. High specificity and sensitivity has also been reported when monitoring the glucose levels only. It is unproven why the glucose level drops when a vascular pedicle is compromised; it is however logically hypothesised, that decreased or terminated blood flow in a flap leads to depletion of the tissue glucose supply[42,113,168-170]. The major limitation of MD however is its high cost. Continuous *pH monitoring* was first introduced in 1983 by using an implantable, removable pH probe[36]. The method has so far not provided reliable diagnosis of vascular thrombosis, but a fall in pH below 7.30 in the flap or a difference of more than 0.35 pH units between the flap and a control area have been suggested as criteria indicating arterial or venous compromise[37,114,171]. Only a few animal and small clinical pilot studies have been conducted to date and no benefit over other methods has been reported.

Technical support methods utilise a readily accessible *Internet* and ubiquitous *personal smartphones with an inboard camera.* This represents an opportunity to monitor MF at a distance and enable rapid communication between nursing and surgical staff reducing the response time to remedial surgery[39]. Although these support methods do not introduce any new innovative idea, procedure or device, they can have a surprisingly high impact on the overall survival and successful salvage rate of the flap. Two studies reported an improved flap salvage rate from

50% to 100% and response time-to-action (recognition-to-re-explorative surgery) reduced significantly from 75 min to 24 min in the first and from 180 min to 8 min in the second study[172-174]. Another advantage is to allow efficient examination of a MF for patients distant from their care provider[38]. *Eulerian video magnification* for non-invasive flap monitoring has also been reported. It is a special technique for enhancing video to reveal nearly invisible changes in colour and motion. One case of monitoring a latissimus dorsi-serratus anterior-rib composite flap was reported with the conclusion that this technique is able to detect changes in perfusion without the clinician needing direct contact with patient. There are significant limitations however, the subject and the camera need to be relatively motionless and adequate lightening (both intensity and rendition) needs to be maintained or reproduced for accurate comparison[175]. Subsequently a *smartphone application* was developed that enables comparative analysis of digital photography for colour differences and it was reported to have 94% sensitivity and 98% specificity in detecting vascular compromise[40]. However this new era of using the Internet and smartphone photography is complicated by possible legal issues around patient-identifiable information and it's storage, transfer, security and ownership rights[176].

DISCUSSION

The ideal monitoring method

Creech defined principal criteria for MF monitoring, stating that an ideal monitoring technique should be:

a) harmless to the patient and flap,
b) rapid, repeatable, reliable, recordable, and rapidly responsive,
c) accurate and inexpensive,
d) objective and applicable to all kinds of flaps,
e) equipped with a simple display that could alert relatively inexperienced personnel to the development of circulatory impairment[177].

An ideal monitoring technique therefore should be easy to apply, objective, continuous, non-invasive, safe, inexpensive, easily and validly interpreted by medical and nursing staff and cost-effective[18,42,177]. More than 40 monitoring methods have been reported over a 45-year period of using MF's, the first of course being DVM. DVM evaluates multiple specific characteristics, it is simple, cheap, does not require special devices and can be reliably done by any experienced medical staff member. With regular DVM we are able to achieve flap salvage rates up to 80% and overall success rates of up to 99% (ref.[17,122-128]).

From the collection of reported monitoring methods it is apparent that for monitoring of buried and semi-buried flaps there are only a limited number of methods that are pragmatic. Those are methods that can be used when there is no direct access for DVM. All of them however require special equipment and are of course more expensive. Some of them; angiographies and nuclear medicine methods are moreover not suitable for continuous monitoring and makes them unlikely to be helpful if salvage is deemed the primary objective of monitoring.

The benefit of other methods over direct visual monitoring

Many studies had focused on various techniques for monitoring the MF but it is necessary to point out, that the actual purpose of observing the flap viability is to improve the salvage success rate and overall free flap success rate. The crux of the issue therefore is timely and reliable detection of a flap compromise that allows effective explorative surgery leading to salvage of the flap[178]. The reason therefore to explore alternative techniques to DVM is to find a reliable technique in cases where DVM is not possible or to find a technique that delivers a better salvage and overall success rate.

Moubayed however, reported that overall flap success rate in head and neck reconstruction was 95% whatever monitoring method was used. But the salvage rate ratio (:) to false-positive rate in percentage were 95:0 for near infrared spectroscopy, 81:10 for implantable Doppler and 61.5:0.4 for DVM (ref.[18]).

A comprehensive review of studies considering MF monitoring published by Chae in 2015 suggests that:

a) Despite the fact that the flap salvage rate is the most important attribute of a monitoring technique to indicate its value and usefulness, this particular information received the least attention by the authors.
b) There are a few reports claiming that the device used to determine flap circulation compromise, did so earlier than DVM but this statement was not associated with improved flap salvage rates or other objective outcomes.
c) Only a limited number of monitoring techniques have shown any evidence for improvement of flap salvage rates over DVM namely; implantable Doppler probes, near infrared spectroscopy, laser Doppler flowmetry, quantitative fluorimetry and digital smartphone assessments.
d) However none of those studies reached the level of scientific evidence that would enable inclusion for widespread clinical use at that time[3].

In the Table 3 we summarise the reported benefits of various methods over DVM considering early detection of flap alteration that can lead to successful salvage of a truly compromised flap.

Only Doppler ultrasound, laser Doppler flowmetry and near infrared spectroscopy were reported to produce better salvage rates and the possibility of earlier detection of vascular compromise of the micro-vascular flaps.

Selected methods other than DVM that have been suggested to have the characteristics of an ideal monitoring device are DUS, LDF and VLS. Also many reports claim that some methods determine flap compromise earlier than DVM, however they did not proceed to validate that this leads to improved flap salvage or any other measurable improved outcome. Comprehensive and detailed reviews however suggest that only implantable DUS probes, NIS, LDF, quantitative fluorimetry and smartphone assessments have shown any evidence for improvement of

Table 3. Monitoring methods and reported benefit over clinical visual assessment.

Monitoring method	Higher salvage rate	Earlier detection
Surface skin temperature (surface or implanted)	–	–
Bromphenol blue	Not reported	Not reported
Pinprick glucose testing	Not reported	Not reported
Doppler ultrasound (implantable probes)	+	+
Doppler ultrasound (handheld)	Not reported	Not reported
Colour Doppler	Not reported	Not reported
Contrast enhanced ultrasound	Not reported	Not reported
Laser Doppler flowmetry	+	+
Electromagnetic flowmetry	Not reported	Not reported
Confocal laser scanning microscopy	Not reported	Not reported
Laser speckle contrast imaging	Not reported	Not reported
Visible light spectroscopy	Not reported	+
Microlightguide spectrophotometry	Not reported	Not reported
Diffuse correlation spectroscopy	Not reported	Not reported
Diffuse reflectance spectroscopy	Not reported	Not reported
Near infrared spectroscopy	+	+
Pulse oximetry	Not reported	+
Multispectural spatial frequency domain imaging	Not reported	+
Luminiscence ratiometric oxygen imaging	Not reported	Not reported
Fluorimetry	+	Not reported
Orthogonal polarised light	Not reported	Not reported
Compound muscle action potentials	Not reported	Not reported
Contractility/electromyographic activity	Not reported	–
Photoplethysmography	Not reported	Not reported
Intraparenchymatous venous pressure monitoring	–	Not reported
Invasive temperature monitoring	Not reported	Not reported
Tissue oxygen tension	Not reported	Not reported
Impedance plethysmography	Not reported	Not reported
Side-stream dark field imaging	Not reported	Not reported
Hydrogen clearance	Not reported	+
Angiography	Not reported	Not reported
Scintigraphy	Not reported	Not reported
Positron emission tomography	Not reported	Not reported
Radioactive microspheres	Not reported	Not reported
Xenon washout	Not reported	Not reported
Micro-dialysis	Not reported	+
Glucose-lactate levels	Not reported	+
Continuous pH monitoring	Not reported	Not reported
Digital photography /camera	Not reported	+

flap salvage rates over DVM. None of the reports of the aforementioned methods however reached the level of statistical validity that would enable a particular technique to be approved for widespread clinical use[3,39, 54,89,90,94,95,167,172]. Mostly the studies report some benefit of a new method however about 50% of studies also report adverse findings such as additional expenses, technical/training issues and misdiagnoses leading to poorer outcomes overall[176].

Current general clinical practise is to monitor non-buried flaps by DVM usually supported by one other method; DUS (most often), LDF, spectroscopy or plethysmography[3,179]. Simultaneous use of two methods however presents a surgical dilemma when there is disagreement between the indications of each method. For buried and semi-buried flaps the most units utilise an implantable DUS probe. However, the disadvantage of devices using implantable probes is that even minor movement of the device within the patient alters the signal so they are more prone to give false results due to simple probe displacement or technical failure. Also there is a risk of inadvertent premature probe removal or unwanted forces on anastomoses by the transduction wire or probe that can lead to vessel kinking or compression[20]. Another option for buried flaps evaluation is the use of an externalised part of the flap as visual monitor – skin, muscle or other. This technique is feasible in almost all kinds and types of MF and enables one to use all the advantages of DVM with or without implementation of other methods.

The optimal monitoring frequency

The optimal frequency of MF monitoring is unclear and is not generally defined nor is there an accepted standard. It is highly variable and often it is adapted to individual patient/surgery conditions, surgeon experience or surgical unit historical routine use. However multiple recommendations were reported during last decades. The British Association of Head and Neck Oncology Nurses recommends for routine non-complicated cases monitoring every 15 min for the first 6 h, then 30 min for the next 18 h, hourly for the next 48 h and then individually[119]. Another recommended schedule is hourly monitoring by nursing staff for the first 48 h and then 2-hourly simultaneously with medical monitoring every 4 h for first 48 h and then 8-hourly[118,180]. Chae advocated half-hourly for the first 24 h, hourly for the next 24 h, 2-hourly for the next 24 h and 4-hourly thereafter[3]. Yet another protocols advise hourly monitoring for first 72 h[120,180]. Zoccali recommend hourly evaluation for the first 48 h and then it be reduced to 6 hourly[5]. In our department the routine protocol for standard non-complicated cases is monitoring hourly for first 3 days and then 4 hourly until the patient is dismissed (usually 7-10 days after surgery).

The optimal monitoring period

Zoccali et al. reported, that when flap discomfort occurs more than 48 hours after surgery the salvage procedure usually fails. He concluded that late flap compromise is more likely due to some flap-internal failure rather than that of vascular pedicle origin and attempted salvage surgery may not be worthwhile. Therefore he proposed that monitoring of the MF is very important during the first two days and the salvage surgery should be carried out whenever there is a suspicion in this timeframe. However continuing monitoring past this point is debatable as re-exploration should be considered prudently[5]. Another authors support this thesis[26]. They suggest the first 72 h after free flap surgery is the critical period. Arterial occlusion occurs usually within first 24 h, venous congestion between 24-72 h. There is little evidence supporting continued MF monitoring after the initial three days.

Patient's perception of flap monitoring

Creech's criteria for an optimal monitoring method states that; it should be harmless to the patient and the flap[177]. However, we need to consider not only the physical safety of patient but also their psychological comfort and acceptance. Significant patient distress can lead to consequences at the microcirculatory level ending with vascular spasms. This was proved in coronary arteries and can be applied to other vessels too[181]. Spasm of vascular pedicle can of course result in thrombosis especially at the site of anastomosis.

A questionnaire-based study concludes that generally patients are not worried by observation but about 30% reported disturbed sleep and 50% would appreciate fewer observations when asleep[182]. Again about 50% feel relief when the monitoring changes from hourly to four-hourly. Saldago et al confirmed that frequent periodical flap monitoring that is usual within few first days after surgery can be distressing and in predisposed persons can lead to psychological discomfort with possible consequences in flap circulation alteration[183].

The financial aspects of monitoring

The clinical benefit of various methods of MF monitoring is crucial and is the prime focus of published studies. However, financial aspects are becomingly increasingly important as there is more competition for resources and the cost of sophisticated equipment and specialist operators increases. In 1975 Creech suggested that the ideal monitoring method should be selected using benefit to the patient as the only criteria[177]. However in 2010 Sakakibara and then in 2016 Moubayed reported that cost effectiveness should also be taken into account[18,42]. It is generally accepted that the worlds public healthcare systems are becoming more and more financially demanding and funds needed to cover medical care are increasing rapidly. A major contributor to this is new and expensive technologies implemented in medicine to deliver better outcomes.

The cost of each method can be broken down into direct and indirect expenses. Direct expenses include special equipment (probes, transmission wires, monitors, cameras, computers, ultrasounds, lasers, laboratory or other devices and the like) and general consumables (gloves, swabs, syringes, needles, sutures, disinfection solutions, ultrasound gel, reagents etc.) Indirect expenses are more difficult to estimate precisely and are also challenging to discover in total. They include but are not limited to such things as staff costs, power costs, expenses related creating and running specialised units or laboratories, building of special facilities or updating existing facilities to comply with progressing safety standards, services and calibrations of machines but also things like phone calls, Internet, costs of special smartphone applications etc.

A financial costing of a proposed method is however rarely reported. Generally where there is some consideration, only direct expanses are mentioned. For example the cost of one tissue oximeter single use implantable probe is about 600 USD, the cost of a colour Doppler ultrasonography machine is between 30.000 – 225.000 USD (ref.[20]). Looking at direct expenses only for DVM, the initial outlay is near 0 USD and per patient are near 0 USD, for handheld Doppler costs are initially100 USD and 0/patient, for implantable Doppler initially 3.100 USD and 400/patient and for near infrared spectroscopy initially 19.500 USD and 650/patient[18]. Poder in 2013 estimated the personnel costs per flap using an implantable Doppler were approximately 200 CAD (ref.[184]). In 2015 Chae reported the total cost for micro-dialysis to be about 597 USD/patient[3].

In our search, we found only one comprehensive paper related to cost-effectiveness of MF monitoring and it only considers DVM. The cost of DVM in 2016 has been calculated to be 193AUD per case considering staff time, equipment and materials. The authors calculated the costs of a salvage procedure as 1.015 AUD per hour and the costs of a replacement surgery as 5.075 AUD. When considering total cost-effectiveness the study revealed an alarming outcome. DVM of all the evaluated flaps totalled 25.476 AUD and did not lead to the successful salvage of a single MF (ref.[185]). They performed hypothetical calculations using a base of 400 MF's with or without monitoring and assumed two regimes, firstly a salvage rate of 60% and failure rate of 7.5% and secondly a salvage rate of 60% and failure rate of 0.7%. This resulted in the overall costs for 400 monitored flaps being higher than for 400 flaps without monitoring just simple replacement of necrotic flaps in both regimes.

When considering the cost-effectiveness of any monitoring method it must clinically or economically improve or beneficially change the outcome in some way. Should the failure rate of MF be zero, monitoring is neither cost-effective nor beneficial. It follows logically, that monitoring can be cost-effective only when there is quite a high frequency of vascular failure and the outcome of monitoring is maximal salvage success rate and minimal replacement surgery. In general, the rate of MF compromise or loss is relatively low and therefore blanket monitoring of all MF's cannot be cost-beneficial even when using simple DVM. This might lead us to conclude that we should consider selective use of monitoring only in high-risk patients or technically difficult flaps. There are however two reasons why this is not possible; (a) there is a wide spectrum of causes of MF failure and some of them are surgeon-independent and (b) there are no reliable criteria on how to define a true high-risk patient or MF from the point of view of MF failure. However, it has been suggested, that a way to diminish the financial burden is to reduce the frequency and longevity of flap monitoring[5,26].

In general we have yet to accept that the principal benefit of universal monitoring of the MF is psychological for both staff and patient and that by monitoring all MFs, we are able to detect flap compromise with a successful salvage procedure in some cases, that no doubt is highly beneficial for that particular patient.

CONCLUSION

The use of MF has been a clinical reality for over 45 years and currently it is a well-established method that is applicable to a wide range of reconstructive cases. Despite the continuing refinement of microsurgical techniques and the ongoing development of devices and materials, some failures of the MF are likely to occur. In the last decade, the rate of re-operation and flap loss of 5-10% remains basically unchanged. This is because there is a wide array of factors that are responsible for flap failure and some of them are impossible to eliminate and are far beyond the control of the surgeon. However, there are still complications that can be reversed by re-explorative surgery when it is implemented in an appropriate time frame. This highlights a real need for reliable continuous monitoring of free flaps.

Over 40 methods of MV monitoring have been presented during the 45-year history. The ideal monitoring method was defined as (a) harmless to the patient and flap, (b) rapid, repeatable, reliable, recordable, and rapidly responsive, (c) accurate and inexpensive, (d) objective and applicable to all kinds of flaps, (e) equipped with a simple display that could alert relatively inexperienced personnel to the development of circulatory impairment and (f) cost-effective.

DVM is still generally used and accepted as a standard, easy to perform and reliable method. It evaluates the actual flap condition and the dynamics of changes. The reason for inventing and testing any new method should be to find a reliable technique in cases where direct visualisation is not possible or to find a technique that is more reliable and offers better salvage and overall success rates. Though some methods are considered to be ideal as they are non-invasive, simple, relatively inexpensive, specific and easily evaluated by medical and nursing staff, valid scientific evidence supporting their superiority over DVM is still missing. A further concern is the financial impact of monitoring methods on an already increasingly cost conscious healthcare system. Although in human medicine, cost-benefit is generally not considered as the highest priority, financial consequences are becoming more and more pronounced.

In clinical settings, usually microsurgical units implement DVM alone or with some supporting method such as DUS, LDF, plethysmography or spectroscopy. For buried flaps, handheld DUS or an implantable DUS probe is used.

To date, there is no alternative that can entirely supplant DVM. The effectiveness of DVM can be potentiated using any of the technical support methods referred to above. In this review, we find that there is a persistent belief that DVM possesses optimal characteristics – balanced effectiveness, safety and costs. For these reasons, we conclude that for buried and semi-buried flaps use of an externalised part of the flap as monitor is highly advocated.

Search strategy and selection criteria

Our search strategy was to collect all reported methods of monitoring of micro-vascular flaps and to evaluate their benefits over the simple and generally used direct visual monitoring. Scientific articles from 1975-2019 were searched using the PubMed database and we found 1.300 pertinent articles. Search terms included; free flap monitoring, micro-vascular flap monitoring, microsurgical flap monitoring and free tissue transfer monitoring. Exclusion criteria were (a) duplicate references, (b) references where flap monitoring was peripheral to the topic and (c) invalid or irrelevant references. After applying the exclusion criteria we were left with 356 valid articles on which this review is based.

ABBREVIATIONS

MF, Micro-vascular flap; DVM, Direct visual monitoring; LDF, Laser Doppler flowmetry; SST, Skin surface temperature; DUS, Doppler ultrasound; VLS, Visible light spectroscopy;, NIS, Near infrared spectroscopy; PO, Pulse oximetry; EMG, Electromyography; PPG, Photoplethysmography; CT, Computed tomography; MRI, Magnetic resonance imaging; SG, Scintigraphy; PET, Positron emitting tomography; MD, Micro-dialysis.

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