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Advancements in Free Flap Monitoring in the Last Decade: A Critical Review

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Background: The authors conducted a review of the recent literature on the monitoring of free flaps to create an overview of the current monitoring devices and their potential as an ideal monitoring method.

Methods: A literature-based study was conducted using the PubMed and Cochrane databases. The following search terms were used: “flap” and “monitoring.” All monitoring methods found between January of 1999 and January of 2009 were evaluated. Monitoring methods that were described in five or more clinical reports were further investigated.

Results: The advantages and disadvantages of conventional monitoring methods, the implantable Doppler system, color duplex sonography, near-infrared spectroscopy, microdialysis, and laser Doppler flowmetry are presented. Furthermore, an overview is given of their potential as ideal monitoring method.

Conclusions: The implantable Doppler system, near-infrared spectroscopy, and laser Doppler flowmetry appear to be the best monitoring devices currently available. As most of the publications on monitoring have focused on the reliability of the systems, future research should also address their cost efficiency. (*Plast. Reconstr. Surg.* 125: 177, 2010.)

Since its introduction in the late 1950s,¹ the free flap has evolved to the method of choice as a means to reconstruct or close large defects. In the last decade, success rates of 95 percent and higher have been reported.²⁻⁴ Despite these improving success rates, microvascular failure remains a costly disaster. As salvage rates have been reported to be inversely related to the time interval between the onset of ischemia and its clinical recognition,⁵ the monitoring of free flaps remains of major importance. In 1975, Creech and Miller⁶ described what the ideal monitoring device should be like. It should be harmless to patient and flap, rapidly responsive, accurate, reliable, and applicable to all types of flap. Furthermore, it should be equipped with a simple display so that even relatively inexperienced personnel can alert the development of circulatory impairments. Despite the introduction of various new and improved techniques, none of these techniques has succeeded to meet all these so-called ideal criteria.

We conducted a review of the recent literature on free flap monitoring to create an overview of the current monitoring devices and to define the ideal monitoring method.

METHODS

A literature-based study was conducted using the PubMed and Cochrane databases. The following search terms were used: “flap” and “monitoring.” All monitoring methods found between January of 1999 and January of 2009 were evaluated. Monitoring methods that were described in five or more clinical reports were further investigated. Only studies written in the English language were included. For historical and technical backgrounds, reports older than 1999 were used whenever considered necessary.

The number of hits per monitoring method and the properties of the different publications are described in Table 1. No head-to-head comparison of monitoring methods was found. In selecting data about the reliability of the system,

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Table 1. Number of Hits per Monitoring Method and Characteristics of These Publications

	Conventional Methods	Implantable Doppler System	Color Duplex Sonography	Near-Infrared Spectroscopy	Microdialysis	Laser Doppler Flowmetry
No. of hits	19	10	10	8	6	6
No. of trials	5	7	8	6	4	5
No. of prospective trials	3	0	5	6	3	3
Mean population per trial (range)	33 (8–67)	91 (5–369)	21 (5–54)	29 (11–41)	34 (14–78)	87 (11–232)
Types of reconstructions reported in trials						
Head and neck	—	3	2	1	1	1
Breast	—	1	1	4	1	1
Extremities	—	1	1	1	—	—
Buried	4*	1	4	—	1	—
Comb.	1	1	—	—	1	3

Comb., reconstructions at different anatomical locations.

*Although these reports describe monitoring buried flaps, they do this by adding an external component, making them not completely buried flaps.

obviously prospective trials with a large population were preferred over others.

Data Analysis

Data are presented as positive predictive value (chance that the flap is indeed compromised when a change of signal occurs) and negative predictive value (chance that the flap is not compromised when a normal signal remains). Cases in which the signal changed (whatever the reason) while the flap was not compromised were rated as false positive. Cases in which the signal did not change while the flap was compromised were rated as false negative. If the monitoring device gave a change in signal in a compromised flap, but this compromise was not noticed otherwise by the medical staff, it was rated as true positive.

RESULTS

Conventional Methods

Conventional monitoring methods include clinical assessment of skin color, turgor (especially in replants) and temperature of the flap, and capillary refill. Handheld Doppler may also be regarded as a conventional technique.^{7,8}

Current technologic advances in media and the Internet inspired some authors to use regular digital images to monitor color. It can help detect changes in time more quickly. Another advantage is that images can be transmitted via the Internet to the consulted surgeon at home. In dynamic processes, a video recording can be made as well.^{9,10} To monitor color, buried flaps can be given an external component (either skin¹¹ or a vessel stump¹²). These can be removed later dur-

ing a secondary procedure. Nevertheless, monitoring the color of muscle flaps covered by a skin graft remains cumbersome and not infrequently vascular problems are not signaled in time to allow for successful reintervention.

The temperature can be monitored using touch, temperature probes,¹³ temperature-sensitive tape¹⁴ (Fig. 1), and a handheld noncontact thermometer.¹⁵ Surface temperature monitoring is regarded by some authors to be of value only in monitoring replantations and small free flap reconstruction because of its inability to detect changes before flap failure or reoperation in deep inferior epigastric perforator flaps.¹⁶

Fig. 1. Temperature strip monitoring (Sharn Anesthesia, Inc., Tampa, Fla.) on a deep inferior epigastric perforator flap used for microsurgical breast reconstruction. One strip shows the temperature of the flap, while the other strip registers the temperature of the contralateral breast.

To aid postoperative localization of the vessels by Doppler, the anastomotic sites are often marked on the skin by ink. A transparent film dressing can be used to protect the mark from fading during the patient's inpatient stay.¹⁷

Implantable Doppler System

The implantable Doppler system is an invasive technique that allows direct and continuous monitoring. The technique was introduced in 1988 by Swartz et al.¹⁸ in microsurgical reconstructions.

The system consists of an implantable 20-MHz ultrasonic probe that is mounted on a silicone cuff that can be wrapped around the venous pedicle¹⁹ and a battery-operated portable monitor. Different methods have been described to attach the cuff around the vein, including microclips,²⁰ sutures,²¹ and fibrin sealant,²² all with good results. Postoperatively, the surgeon, nursing staff, and the patient are able to hear the audible venous signal. The ultrasonic Doppler crystal is connected to a thin wire through which it exits the wound. The wire is plugged into the monitor at the patient's bedside. The electrode slides free from the cuff when pulled externally at 5 to 10 days postoperatively, depending on the length of monitoring required. The electrode is designed to separate from the cuff when a tension of 50 g is applied^{18,19} (Fig. 2).

The system has been praised for its ease of use, value in buried flaps, and the information it offers during the inset of the flap.^{23–27} Difficulty in the interpretation of back and forth motion of blood

in the internal mammary vein, however, may occur. This can be tested by listening if the signal stops after clamping the vein. If the signal does not, the system is of less use.²⁸ The negative predictive value of the implantable Doppler system is reported to be 100 percent.^{21,25,26,29} In one reported case, the signal remained while the pedicle was kinked. In this case, the cuff was, however, wrapped around a vein in which two perforators drained, which explains the remaining signal.³⁰ The positive predictive value in a study including 369 head and neck cases was 81 percent.²⁴ Another study on 121 breast reconstructions described a positive predictive value of 93 percent.²⁵ In reports in which the system is used not exclusively for the vein but for monitoring either artery or vein, this number has been reported as low as 18 percent.^{26,29} The costs of the system consist of \$3100 for the monitoring box and \$412 for each disposable probe.³¹

Color Duplex Sonography

Color duplex sonography is a noninvasive monitoring technique that combines the recording of blood flow velocity with the recording of blood flow direction. Combined color flow and spectral Doppler imaging within both flap and recipient vessels enables accurate assessment of anastomotic patency (Fig. 3).

Color duplex sonography is often used in buried flaps and head and neck reconstructions, because in these circumstances, flaps cannot possibly be monitored with conventional methods.^{32–37} Its strength is the precise and quantitative characterization of inflow and outflow,³⁸ and it has been reported to pre-

Fig. 2. The implantable Doppler system (Cook Medical, Cook Ireland Ltd., Limerick, Ireland) showing the silicone cuff around the vein before skin closure. The Doppler crystal (which is attached to the cuff) is connected to a thin wire through which it exits the wound.

Fig. 3. Color duplex sonography showing the monitoring of a buried gracilis flap. Figure 3 has been given to us by Cook Medical and is free to access on their site.

vent unnecessary revisions.³⁵ The technique, however, requires experience with the device, as well as detailed knowledge of the recipient site and flap. This means that in some cases the radiologist and microsurgeon both have to be available when assessing the flap.³³ This explains why in several reports the system is often used no more than once a day.^{34,35,37,38} Color duplex sonography has also been used as complementary test in studies addressing near-infrared spectroscopy^{39,40} or the implantable Doppler system.²⁹ Two studies, with a combined population of 65 cases of head and neck reconstructions and buried flaps, reported the positive and negative predictive values of 100 percent.^{33,38} The cost of the color duplex system may vary from \$30,000 to \$225,000, depending on its specifications.⁴¹

Near-Infrared Spectroscopy

Near-infrared spectroscopy is a noninvasive technique, which allows continuous monitoring of flap tissue oxygenation and perfusion. It was first described by Jöbsis⁴² in 1977 in the exposed heart and brain, and was first reported in a plastic surgical journal in 1995 to monitor flaps and limbs in rabbits.⁴³

Near-infrared spectroscopy employs the principles of optical spectrometry to measure hemoglobin content and oxygenation in local tissues. The system delivers selected and calibrated wavelengths of near-infrared light via a probe attached to the skin to tissues. Because of the applied technique, the monitoring is not influenced by movements of the probe, like for example in laser Doppler flowmetry.⁴⁴ Selective light absorption by oxygen-dependent tissue chromophores, primarily hemoglobin, results in the reduction of light intensity. The attenuated optical signal exiting the tissue is analyzed using spectrophotometric principles that relate light absorption to the tissue concentration of the chromophore.⁴⁵

Characteristic absorption spectra of oxygenated and deoxygenated hemoglobin permit the system to calculate concentration of both hemoglobin forms.⁴⁶ The tissue penetration depth of near-infrared light can be up to 20 mm⁴⁴ (Fig. 4).

Near-infrared spectroscopy is reported to allow objective and early detection of flow failure. It can accurately identify early signs of arterial and venous thrombosis before clinical signs of flap failure.^{44,47} In the first few postoperative hours, however, there can also be a slight physiological decrease in oxygen saturation, which should not be misunderstood as a vascular complication. Af-

Fig. 4. Near-infrared spectroscopy showing the preoperative calibration of the device in a deep inferior epigastric perforator flap reconstruction.

ter 12 hours, the oxygen saturation returns to normal levels.^{40,47} While some authors prefer near-infrared spectroscopy for flaps with a cutaneous component,⁴⁴ others also advocate its use in buried flaps.⁴⁷ Three studies, with a combined population of 98 patients, reported both positive and negative predictive values of 100 percent.^{44,47,48}

The cases reported in these studies included head and neck and breast, as well as buried flaps. The costs for a near-infrared spectroscopy monitoring system are \$16,500 for the monitoring box and \$150 for the disposable sensor.⁴⁹

Microdialysis

Microdialysis is an invasive, intermittent, indirect monitoring technique. It was first described by Delgado et al.⁵⁰ in 1972 for detecting neurotransmitters and ischemia in monkeys. In 1998, Røjdmark et al.⁵¹ reported its use for monitoring myocutaneous flaps.

Microdialysis is a sampling technique that studies the biochemistry of organs or tissues. A double-lumen microdialysis catheter or probe similar in size to an 18-gauge venous cannula is placed (using an open needle) under direct vision into the tissues. It is connected to a small pump, which infuses physiologic fluid through the catheter. Across a dialysis membrane, this fluid equilibrates with the interstitial fluid surrounding the catheter, and therefore aliquots of the perfusate can be analyzed on the tissue content of glucose,

lactate, pyruvate, and glycerol metabolite concentrations. A falling glucose and rising lactate-to-pyruvate ratio indicates anaerobic metabolism and thus indicates an arterial compromise.⁵² A rising glycerol level reflects cell membrane damage and is seen in both venous congestion and arterial compromise⁵³ (Fig. 5).

Microdialysis is capable of detecting vascular complications before clinical signs of vascular compromise.⁵⁴ A learning curve, however, is required to optimize the use of the system.⁵⁴ Besides, it takes 30 minutes to get a reading (20 minutes to fill the microvial and 10 minutes to analyze the fluid).⁵⁵ Microdialysis can be of extra value in buried and intraoral flaps.^{55–57} The reported positive predictive value of microdialysis varies. In a study containing 78 consecutive flaps located at different anatomical locations, a positive predictive value of 90 percent was noted.⁵⁴ In another study of 25 head and neck reconstructions, however, the positive predictive value was reported to be 22 percent.⁵⁷ Although this percentage is low, it could have been caused by the learning curve of the system.⁵⁷ Both studies reported a negative predictive value of 100 percent.^{54,57} The cost for the analyzer/monitor itself is almost \$52,000; the additional costs including catheters, reagents, and consumables are \$570 per flap.⁵⁸

Laser Doppler Flowmetry

Laser Doppler flowmetry provides a noninvasive continuous means of determining tissue per-

fusion. One of the first reports on laser Doppler flowmetry was an experimental animal study by Riva et al.⁵⁹ in 1972 to measure the blood flow in the retinal artery of albino rabbits. In 1977, it was reported by Stern et al.⁶⁰ in the assessment of blood flow in human skin.

In laser Doppler flowmetry, tissue is illuminated with coherent laser light through a fiber-optic cable. Backscattered light is collected by the same probe, and a frequency shift is extracted by the heterodyne light beating technique. The power-spectral density of shifted light is a linear function of the average velocity of moving cells within the tissue. Depending on the probe geometry, a detection of blood flow and flow velocity up to 8-mm depth is possible.⁶¹ The probe can be attached to the skin by using double-sided adhesive rings; sutures can also be used when a firmer attachment is required⁶² (Fig. 6).

It is more important to observe trends in laser Doppler flowmetry readings rather than the absolute value, particularly in cases of venous occlusion, in which there is typically a less abrupt decline in flow values.^{63,64} The system can be sensitive to vibration, motion of the probe, or tissue. If the flowmeter indicates an abnormal blood flow, just repositioning of the probe can improve the flow readings.⁶² To better evaluate the microcirculation of the flap, laser Doppler flowmetry has been used with light guide reflectance spectrophotometry.²⁶ To more effectively differentiate between arterial occlusion and venous congestion, it has been used in combination with tissue spectrometry with good results.⁶¹ Two large studies, with of a combined population of 326 cases, showed a negative predictive value of 100 percent and positive predictive

Fig. 5. Microdialysis monitoring of a muscle flap covered by a split skin graft. The catheter is inserted into the flap and secured by sutures. A microvial is connected to the catheter to collect the fluid. An advantage of microdialysis, shown here, is that the catheter can be inserted next to the flap and tunneled to it subcutaneously, preventing interference between monitoring and wound dressings.

Fig. 6. Laser Doppler flowmetry monitoring of a deep inferior epigastric perforator flap reconstruction.

value between 94 and 100 percent.^{62,63} The cases in which the probe had to be repositioned are, however, not included in these numbers.^{62,63}

The price of the laser Doppler flowmeter ranges upward from \$5460, and the price of the probe ranges upwards from \$1015. The probe can be used for at least 10 cases or half a year before it needs to be replaced. The current generation of laser Doppler flowmetry devices have integrated temperature sensors to aid monitoring.⁶⁵

DISCUSSION

Until today, the most commonly applied monitoring methods have been conventional techniques. In only approximately 10 percent of reported cases are other methods used, and in most of those cases the method used is laser Doppler flowmetry.^{66,67} This study was undertaken to create an overview of methods of free flap monitoring in the recent literature to define which monitoring method is currently the best.

It remains difficult to compare trials of different monitoring methods. Methods of investigation and definitions differ widely per study. Furthermore, it is important to realize that each study is being performed in a different setting in which technical skills, type of reconstructions, and experience in free flap monitoring may differ.

Although conventional monitoring methods are cheap, the results of this study do not favor the sole use of these methods when taking into account the response time of the method. The implantable Doppler system, near-infrared spectroscopy, microdialysis, and laser Doppler flowmetry have all been reported to detect a vascular complication earlier compared with conventional methods. A rapid response can often be achieved by a continuous monitoring method, such as the implantable Doppler system, near-infrared spectroscopy, and laser Doppler flowmetry. Microdialysis is not continuous; a microvial has to be inserted to collect a sample, and this sample has to be analyzed. Furthermore, taking into account that the costs of microdialysis are the highest and the output is more difficult to interpret, we do not think it is the best monitoring method available at this moment.

Most research protocols used color duplex sonography only once a day to monitor flaps and used it primarily as a method of control, when in doubt or for buried flaps.^{29,33–35,39,40} We believe that these are the best indications for the use of color Doppler sonography. It is, however, more time consuming compared with most other methods, and trained personnel are needed to interpret the

data correctly.^{33,35} If, however, a vascular compromise is found, especially in buried flaps, the chances for a successful reintervention may be limited, due to an extended ischemic interval.

When comparing near-infrared spectroscopy, the implantable Doppler system, and laser Doppler flowmetry, near-infrared spectroscopy probably has the most potential in becoming the ideal monitoring method. The system is reliable; all reports state a 100 percent positive and negative predictive value,^{44,47,48} and it also gives information on the exact type of complication. Furthermore, near-infrared spectroscopy is noninvasive and is reported to monitor tissue up to 20 mm in depth,⁴⁴ making it applicable to most flaps.

The implantable Doppler system is the cheapest of the newer monitoring methods. Two other important advantages are that it can be used in all types of flaps and that its reading is easy to interpret, because the flow of the vein is reflected as an all or none phenomenon. Therefore, the system may be especially useful for less-trained personnel. What makes the system less ideal is the fact that it is an invasive system and that a component (the silicone cuff) remains behind after removal of the lead and Doppler crystal. Besides, the placement of the system is critical, resulting in the lower positive predictive value.^{24,25}

Laser Doppler flowmetry is a system with similarities to near-infrared spectroscopy but with some differences as well. The penetration depth is reported up to 8 mm,⁶¹ compared with 20 mm with near-infrared spectroscopy.⁴⁴ In addition, instead of looking at an absolute value, one follows trends with laser Doppler flowmetry,^{63,64} as flow and not oxygenation is monitored. This is also why near-infrared spectroscopy is more reliable if the external probe temporarily detaches, because the oxygenation is more equally divided over the flap compared with flow. An advantage laser Doppler flowmetry has over near-infrared spectroscopy is its cost, being less than half of the price of the near-infrared spectroscopy system (Table 2).

As most of the publications on monitoring have focused on the reliability of the systems, future research should address “head-to-head” comparisons of the different monitoring methods as well as the cost efficiency of the systems, especially as it becomes more important to further reduce the costs of healthcare. The cost effectiveness can, for example, be calculated by investigating how the success rate of the free flaps, and in particular the success rate of the revision, changes by the introduction of a monitoring system.

Table 2. Different Monitoring Methods Compared with Criteria of Creech and Miller

Monitoring Technique	Positive Predictive Value	Negative Predictive Value	Continuous	Invasive	Direct	Easy to Interpret	Simple Technique	Applicable to All Types of Flaps	Costs
Conventional methods									
Implantable Doppler system	81–93% ^{24,25}	100% ^{24,25}	+	+	+/-	+	+	+	\$3100 (monitoring box), \$412 (disposable probe) ³¹ \$30,000 to \$225,000 ⁴¹
Color duplex sonography	100% ^{33,38}	100% ^{33,38}	-	-	+	-	-	+	
Near-infrared spectroscopy	100% ^{44,47,48}	100% ^{44,47,48}	+	-	+	+	+/-	-	\$16,500 (monitoring box), \$150 (disposable sensor) ⁴⁹
Microdialysis	90% ⁵⁴	100% ^{54,57}	-	+	-	-	-	+	\$52,000 (analyzer), \$570 (catheters, reagents, and consumables) ⁵⁸
Laser Doppler flowmetry	94–100% ^{* 62,63}	100% ^{62,63}	+	-	+	+/-	+/-	-	\$5460 (laser Doppler flowmeter), \$1015 (probe, per 10 cases) ^{66,†}

*The cases in which the probe had to be repositioned are, however, not included in these numbers.

†The system also includes a temperature probe.

CONCLUSIONS

The results of this study do not favor the sole use of conventional monitoring methods when taking into account the time of response of the method. The implantable Doppler system, near-infrared spectroscopy, and laser Doppler flowmetry appear to be the best monitoring devices currently available. As most of the publications on monitoring have focused on the reliability of the systems, future research should also address their cost efficiency.

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NOTE

The prices named in this article for the different monitoring devices only serve as an indication. It is important to realize that they might vary per country and in time.

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