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Evaluating visual perception for assessing reconstructed flap health

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ABSTRACT

Background: Detecting failing tissue flaps before they are clinically apparent has the potential to improve postoperative flap management and salvage rates. This study demonstrates a model to quantitatively compare clinical appearance, as recorded *via* digital camera, with spatial frequency domain imaging (SFDI), a noninvasive imaging technique using patterned illumination to generate images of total hemoglobin and tissue oxygen saturation (stO_2).

Methods: Using a swine pedicle model in which blood flow was carefully controlled with occlusion cuffs and monitored with ultrasound probes, throughput was reduced by 25%, 50%, 75%, and 100% of baseline values in either the artery or the vein of each of the flaps. The color changes recorded by a digital camera were quantified to predict which occlusion levels were visible to the human eye. SFDI was also used to quantify the changes in physiological parameters including total hemoglobin and oxygen saturation associated with each occlusion.

Results: There were no statistically significant changes in color above the noticeable perception levels associated with human vision during any of the occlusion levels. However, there were statistically significant changes in total hemoglobin and stO_2 levels detected at the 50%, 75%, and 100% occlusion levels for arterial and venous occlusions.

Conclusions: As demonstrated by the color imaging data, visual flap changes are difficult to detect until significant occlusion has occurred. SFDI is capable of detecting changes in total hemoglobin and stO_2 as a result of partial occlusions before they are perceivable, thereby potentially improving response times and salvage rates.

1. Introduction

Free flap reconstruction is often used to repair a variety of complex defects. Success rates in free tissue transfer are reported to be between 91% and 99% at major microsurgical centers [1–6]. Between 5% and 25% of free flaps are reported to undergo reexploration for microvascular compromise or other factors of which 37%–81% are successfully salvaged [3,5,6].

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One potential reason for lower salvage rates may be the delay in determining when flaps are failing because externally visible signs of microvascular compromise often lag behind the inciting event. Numerous studies have demonstrated that earlier detection and intervention for failing flaps is associated with improved outcomes [3,5]. Partial occlusions are particularly difficult to detect and can have significant effects on flow dynamics with only subtlety apparent changes *via* conventional monitoring. Few animal studies focus on studying these partial occlusions [7], yet the ability to detect these early stages of occlusion may be critical for improving salvage rates in compromised tissue flaps [4,5,8].

Many modalities have been developed in an attempt to provide optimal free flap monitoring; however, clinical bedside monitoring is the only ubiquitous standard [4]. Characteristics such as temperature, capillary refill rate, Doppler signal, and color as well as the change in these parameters over time are used to determine when to take a flap back for exploration [4,7,9]. To provide a more quantitative evaluation, several studies have begun to investigate additional techniques to study tissue flaps. Laser Doppler has been used successfully in animals to detect partial occlusions [10], and Doppler ultrasound has been used to monitor tissue flaps postoperatively in humans [11,12]. Near-infrared (NIR) spectroscopy has also proven to be useful in identifying occlusions in animals [13–15] and monitoring humans in a clinical setting [6,16]. The main drawback to point measurement-based techniques is their lack of ability to identify small problem areas over a large area of tissue. The use of imaging techniques such as NIR fluorescence imaging allows perfusion levels in the entire flap to be monitored at once [17]. The drawback of this technique is the need to inject a contrast agent such as indocyanine green each time the target tissue needs to be examined. This can add additional cost and is not ideal for frequent scheduled monitoring because of the limited half-life of the contrast. Spatial frequency domain imaging (SFDI) has been used to effectively quantify physiological parameter changes in flaps [18,19] during complete [14,20] and partial [21] vascular occlusions. It is an ideal tool for studying tissue flaps because it is a noncontact technique capable of quickly acquiring wide field data without the need for an exogenous contrast agent. Although all these techniques have been used with varying levels of effectiveness to study tissue flaps, it is difficult to measure how much benefit they provide beyond what can be assessed by basic human monitoring. This is largely because human monitoring is inherently subjective.

One aspect of human monitoring that is possible to quantify is the color changes associated with a failing flap. Quantifiable approaches to monitor color changes are typically done using point measurement colorimeters, although not prominent in examining flaps, they are commonly used to analyze scars [22,23], port-wine stains [24], and pigmented lesions [25,26]. Recent studies have shown that digital photography can yield similarly effective results to colorimeters when analyzed appropriately [26,27]. This is often done by first normalizing the color images to a standard scale (typically CIELAB) and then interpreting differences in that new scale to quantify changes in color (ΔE). As larger values of ΔE represent large changes in color, it is feasible to set a minimum value of ΔE where human vision can begin to perceive changes in color. This is often referred to as the just noticeable difference (JND), but because perceivable color differences are not perfectly uniform throughout the CIELAB color space, most researchers agree that the JND can be between 1 and 3 [28–31]. Studies that have focused on looking at color changes in the skin have claimed a $\Delta E < 3$ is unnoticeable [32]. In this study, we quantified the color changes associated with swine tissue flaps undergoing different levels of partial occlusion to see when they would become noticeable, and compared these results with SFDI to more practically assess the benefit of this imaging technique for studying tissue flaps. Although there are limitations in all animal models, human skin is closer to pig skin than any other readily available animal. This is because of similarities in thickness, structure, hair follicles, sweat glands, and subcutaneous fat [33]. However, the lack of pigment in Yorkshire pigs does minimize potential real world complications associated with optical imaging techniques such as SFDI.

2. Methods

These experiments were performed under the University of California, Irvine Institutional Animal Care Use Committee approved protocol #2006-2693. Eight Yorkshire pigs (30–50 kg) were anesthetized with an intramuscular injection of ketamine (20 mg/kg) and xylazine (2 mg/kg), and an intravenous injection of pentobarbital (10 mg/kg). The pigs were mechanically ventilated with oxygen (100%) and isoflurane (1%–1.5%) and body temperature (36°C–38°C) was maintained with a heating pad. Bilateral 12 cm × 7 cm fasciocutaneous pedicled flaps based on the deep inferior epigastric vessels were raised in the abdominal area. To ensure that only one set of vessels would be connected to the flap, all the vasculature between the femoral artery and vein and the flap was ligated except for the branches that led through the deep inferior epigastric artery and vein. A programmable syringe pump (NE-1000; New Era, Farmingdale, NY) injected saline into an occlusion balloon cuff (Docxs Biomedical, Ukiah, CA) causing it to inflate and restrict blood flow whereas an ultrasound probe (TS-420; Transonic System, Ithaca, NY) monitored blood flow. This surgical procedure was performed on both flaps so that one could be used as a control. In four of the animals, the occlusion balloon and flow monitor were attached to the deep inferior epigastric artery (typical diameter around 3 mm) as seen in Figure 1B. In the other four animals, these devices were attached to the deep inferior epigastric vein (typical diameter around 6 mm). Approximately 60 min after the flap was sutured back into place, baseline blood flow was established in both flaps. To create a series of partial occlusions, the occlusion cuff was programmed to inflate until blood flow was reduced by 25% of the baseline value and maintained for 30 min. The occlusion cuff was then deflated for 30 min allowing the tissue flap to recover. This process was repeated for flow reductions of 50%, 75%, and 100% of the baseline values. Specified flow levels were typically reached within 4 min. The blood flow changes recorded during a typical experiment for partial occlusions of an arterial and venous vessel are shown in Figure 1C and D.