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# The Importance of Long-Term Monitoring to Evaluate the Microvascular Response to Light-Based Therapies

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## TO THE EDITOR

Optimization of laser therapy for disfiguring vascular birthmarks is one specific clinical application (Kelly *et al.*, 2005). Current treatment protocols involve the use of high-power pulsed laser irradiation with parameters chosen to induce selective photocoagulation of the targeted blood vessels, a method known as selective photothermolysis (Anderson and Parrish, 1983). Protocol design is based largely on results from numerical modeling studies (van Gemert *et al.*, 1997), which are designed to predict the laser light distribution within the skin and subsequent photothermal response leading toward selective photocoagulation. However, current modeling methods do not incorporate adequately the complex dynamics associated with changes in light absorption due to conversion of hemoglobin to methemoglobin (Barton *et al.*, 2001; Kimel *et al.*, 2005) and convective mixing of blood during pulsed laser irradiation (Kimel *et al.*, 2003), limiting their overall predictive capability. Furthermore, these models do not consider the chronic, biological response of the microvasculature to therapeutic laser intervention, which remains a poorly researched field. Knowledge of the biological response is critical to understand the repair processes initiated with photothermal injury and to assess the ultimate efficacy of the treatment.

Animal models used as a platform to study light-based, microvascular-targeted therapies include the chick chorioallantoic membrane (Kimel *et al.*, 1994, 2003), hamster cheek pouch (Suthamjariya *et al.*, 2004), and rodent dorsal window chamber (Barton *et al.*, 1998, 1999, 2001; Choi *et al.*, 2004; Babilas *et al.*, 2005; Smith *et al.*, 2006). Optical imaging modalities used to evaluate noninvasively therapeutic outcome include video imaging, fluorescence microscopy, Doppler optical coherence tomography, and laser speckle imaging. Typically, short-term (<24 hours after intervention) evaluation of the microvasculature is performed. Babilas *et al.* (2005) proposed that a (1) 24-hour monitoring period allows for evaluation of "delayed biological effects" in the microvascular response to pulsed laser irradiation, and (2) the short-term response correlates well with numerical modeling predictions of photocoagulation. Longer (>24 hour after intervention) monitoring periods usually are not performed with nontumor-bearing window chambers, presumably due to the reduced clarity of the chamber imposed by poor maintenance of window integrity secondary to infection. However, we hypothesized that the short-term response of the microvasculature is a poor predictor of the long-term response. With emphasis on aseptic methods, we have been able to maintain clear window chamber preparations for as long as 45 days after intervention.

**CONFLICT OF INTEREST**

The authors state no conflict of interest.

With this model, we have studied the long-term microvascular response to light-based, microvascular-targeted therapies.

The data presented herein were acquired from adult male Golden Syrian hamsters. The surgery was performed as defined in a protocol approved by the University of California, Irvine, Animal Use Committee. The surgical protocol was a modified version of one described previously (Papenfuss *et al.*, 1979). For all steps, aseptic conditions were maintained. We used wide-field color reflectance imaging and laser speckle imaging (Choi *et al.*, 2004, 2006; Smith *et al.*, 2006) to document and evaluate quantitatively and chronically ensuing blood flow dynamics. In one set of experiments, we irradiated select arteriole-venule pairs with laser pulse sequences to evaluate the efficacy of various therapeutic protocols. In the presented example (Figure 1a), we irradiated an arteriole-venule pair (upper circle in “Before” image) with five laser pulses containing both 532 and 1064nm laser wavelengths and a second pair (lower circle) with a single 532/1064nm laser pulse. Numerical modeling data suggested that both sets of laser parameters should induce photocoagulation in the targeted vessels (Dr Wangcun Jia, unpublished data). The short-term response was characterized primarily by photocoagulation events, with a substantial-to-complete venular flow reduction and considerable arteriolar flow reduction, a trend in agreement with data presented by Barton *et al.* (1999). At 24 hours after intervention, the arteriolar flow (circle in day 1 speckle flow index image) was absent.

At later time points, partial-to-complete restoration of blood flow in these photocoagulated vessels was observed (Figures 1a and b). In general, we observed several microvascular dynamics, including vasoconstriction, vasodilation, and delayed blood flow changes, in both directly irradiated and nonirradiated vessels. We have observed shunting of blood flow to tortuous collateral vessels (i.e., indicated by arrow in day 6 image). Furthermore, we have observed vessel repair within the same position as the original vessel (i.e., indicated by arrows in day 15 and day 21 images), suggesting that the vascular remodeling process may be associated with a “memory”, in agreement with published tumor angiogenesis data (Mancuso *et al.*, 2006).

In a second set of experiments, we evaluated the efficacy of photodynamic therapy as a photochemical method to destroy the microvasculature. Two days after window chamber installation, we installed a jugular vein catheter for intravenous access, injected the photosensitizer benzoporphyrin monoacid ring A, and used 576nm laser light to excite the benzoporphyrin monoacid ring A. The experimental protocol was similar to the one we published previously (Smith *et al.*, 2006). At 24 hours post-photodynamic therapy, we have observed a considerable shutdown of the microcirculation in the entire window (Figure 2, day 1). However, starting at 3 days post-photodynamic therapy, we have observed a progressive, partial recovery of blood flow, illustrating once again the role of the biological response in mediating the ensuing hemodynamics.

Collectively, our data strongly suggest that the short-term (<24 hours) microvascular response to light-based therapeutic intervention differs considerably from the long-term response. We believe this is due to the biological repair response, which is not taken into account in current theoretical models. Such events have not been observed in previous studies on nontumor-bearing window chambers presumably due to tissue regrowth, which we have demonstrated can be minimized with maintenance of an aseptic surgical field. We have observed considerable vascular remodeling events and at least partial restoration of blood flow within initially photocoagulated blood vessels. Our animal model and optical imaging instrumentation allow us to perform chronic evaluation of novel therapeutic approaches designed to alter the microcirculation. Long-term evaluation is probably essential to provide meaningful data that can result ultimately in improved therapeutic

outcome. For such evaluation, laser speckle imaging also can be used to perform “image-guided microscopy”, to assess quantitatively the wide-field microvascular blood flow response to therapy. This information would be useful in judicious selection of specific regions of interest to probe further with higher resolution imaging modalities such as multiphoton microscopy or optical coherence tomography.

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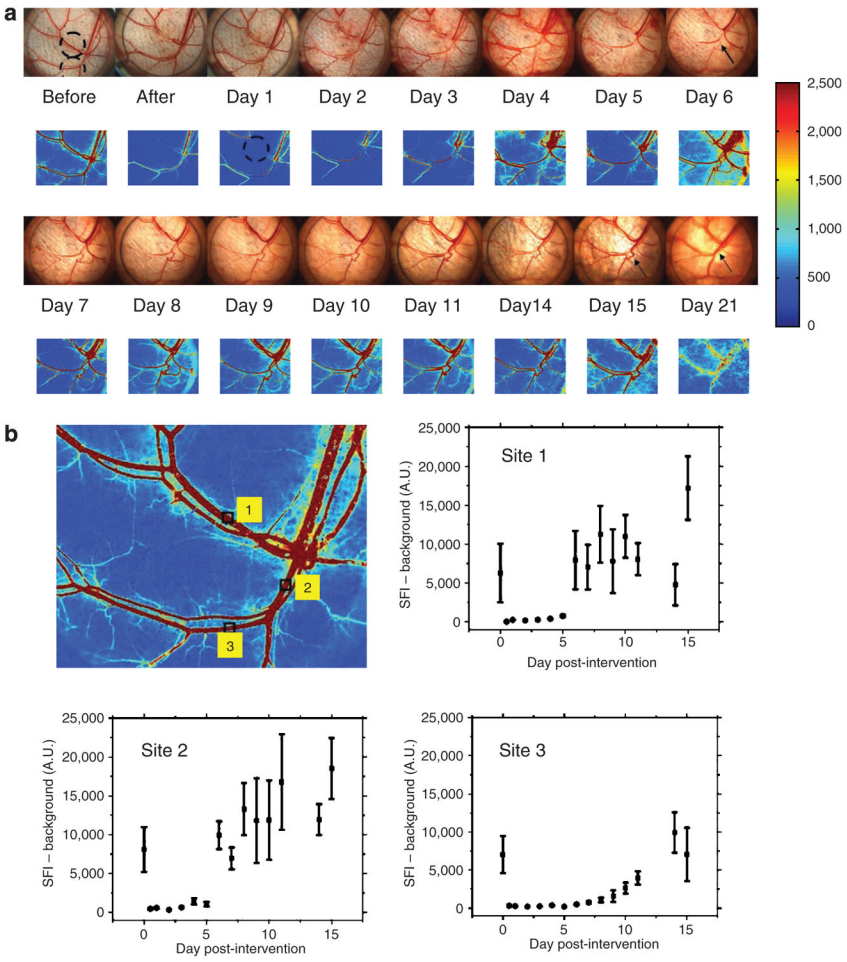


**Figure 1. Microvascular blood flow response after pulsed laser irradiation**

(**a**) Time sequence of wide-field color reflectance images (top row) and corresponding speckle flow index (SFI) images (bottom row) acquired over a 21-day monitoring period after pulsed laser irradiation of selected sites. Two arteriole-venule pairs (dashed circles in "Before" image) were irradiated with simultaneous 532 and 1064nm laser pulses (upper circle—five 1-ms laser pulses at 27 Hz repetition rate, 2 J/cm$^2$ at 532 nm, 3.6 J/cm$^2$ at 1064 nm; lower circle—single 1-ms laser pulse, 4 J/cm$^2$ at 532 nm, 7.2 J/cm$^2$ at 1064 nm). Vascular remodeling and blood flow dynamics were evident during the 21-day monitoring period, with the day 0 and day 21 structural images having similar appearances. (**b**) Quantitative evaluation of selected blood vessel regions of interest. In all three regions, the blood flow was shut down immediately, followed by eventual reperfusion to near-baseline blood flow levels. Color reflectance image dimensions (H×V): 13×10mm$^2$; SFI image dimensions: 9×7mm$^2$.

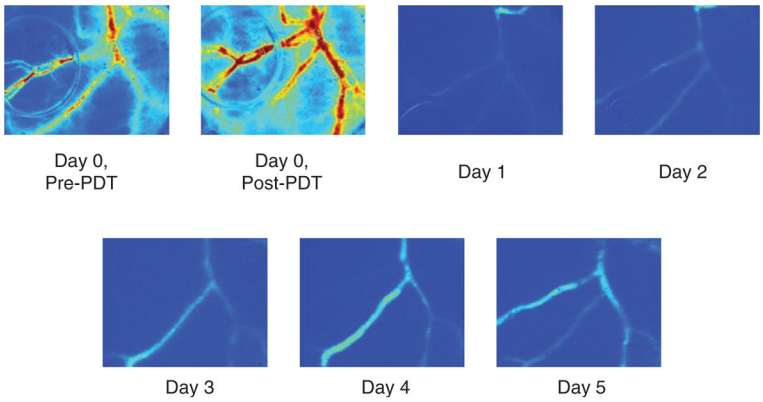


**Figure 2. Microvascular blood flow response, assessed with laser speckle imaging, after photodynamic therapy**

An ~4-mm diameter air bubble was present in the day 0 images, but it had no apparent effect on the speckle flow index (SFI) values. Benzoporphyrin monoacid ring A (1.5 mg/kg body mass) was administered via a jugular vein catheter. Fifteen minutes after benzoporphyrin monoacid ring A injection, continuous wave laser irradiation of the entire window chamber was performed with an argon-pumped dye laser (576 nm, 100mW/cm$^2$ irradiance, 96 J/cm$^2$ radiant exposure). Irradiation was performed on the epidermal side of the chamber. A hyperemic response was observed immediately after photodynamic therapy, consistent with previous data (Smith *et al.*, 2006). At day 1, a large reduction in blood flow was observed, followed by a progressive increase in blood flow in the larger blood vessels. Image dimensions (H×V): 9×7mm$^2$.