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Original Article

Noninvasive imaging analysis of biological tissue associated with laser thermal injury

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ABSTRACT

Background: The purpose of our study is to use a noninvasive tomographic imaging technique with high spatial resolution to characterize and monitor biological tissue responses associated with laser thermal injury.

Methods: Optical doppler tomography (ODT) combines laser doppler flowmetry (LDF) with optical coherence tomography (OCT) to obtain high resolution tomographic velocity and structural images of static and moving constituents in highly scattering biological tissues. A SurgiLase XJ150 carbon dioxide (CO_2) laser using a continuous mode of 3 watts (W) was used to create first, second or third degree burns on anesthetized Sprague–Dawley rats. Additional parameters for laser thermal injury were assessed as well.

Results: The rationale for using ODT in the evaluation of laser thermal injury offers a means of constructing a high resolution tomographic image of the structure and perfusion of laser damaged skin. In the velocity images, the blood flow is coded at 1300 μm/s and 0 velocity, 1000 μm/s and 0 velocity, 700 μm/s and 0 velocity adjacent to the first, second, and third degree injuries, respectively.

Conclusion: ODT produces exceptional spatial resolution while having a non-invasive way of measurement, therefore, ODT is an accurate measuring method for high-resolution fluid flow velocity and structural images for biological tissue with laser thermal injury.

Laser surgery involves high stability and low diffusivity which generates an influx of high energy in a short period of time, and therefore holds a highly important position in studies requiring constancy and precision [1–5]. The increasingly rapid development and progress of laser techniques have been successfully and broadly applied to surgery. However, biological tissues react differently to the absorption and scattering of different light waves, and each wavelength of a laser beam can be used to treat different pathological changes.

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At a glance commentary

Scientific background on the subject

A noninvasive tomographic imaging technique with high spatial resolution is an accurate measuring method for high-resolution fluid flow velocity and structural images for biological tissue.

What this study adds to the field

In our study on laser thermal injury tissue models, the feasibility and potential application of a noninvasive tomographic imaging technique to characterize and image blood flow has been demonstrated.

Noninvasive techniques for imaging *in vivo* blood flow are of great value for biomedical research and clinical diagnostics [6]. In plastic surgery, the superficial dermal plexus alone is particularly affected by the presence of cutaneous disease (e.g., eczema, scleroderma), vascular lesions (e.g., port-wine stain, hemangioma, telangiectasia), or trauma (e.g., irritation, wound, burn, laser). Local blood flow monitoring is also critical for reconstructive surgery involving rotational or free flaps where vascular occlusion occurs in about 5–10% of cases. Early recognition of vascular compromise is essential for the salvage of failing flaps and planning the most suitable time of replanting [7]. One complication in the form of thermal injury that occurs as a result of laser surgery is scar formation [8,9]. In these situations, it would be most advantageous to the clinician if blood flow and structural features could be isolated and probed at user-specified discrete spatial locations in either the superficial or deep dermis. Numerous approaches have been investigated including angiography, electromagnetic flowmetry, and magnetic resonance imaging (MRI), as well as laser doppler flowmetry (LDF) and doppler ultrasound [10–12]. However, a noninvasive technique for *in vivo* blood flow imaging with high spatial resolution is currently not available as a diagnostic tool in clinical medicine.

Optical doppler tomography (ODT) combines LDF with optical coherence tomography (OCT) to obtain high resolution tomographic images of static and moving constituents in highly scattering biological tissues [13–16]. The rationale for using ODT to characterize the underlying microvasculature is that the technique is able to probe with high spatial resolution (2–15 μm) at discrete user-specified locations in biological tissues. Such localization is possible because the detected ODT interference fringe intensity gives accurate discrimination of the optical path length of Doppler-shifted and back-scattered light within the coherence length of source. Furthermore, in contrast to LDF, the overall ODT signal caused from moving red blood cells (RBC) is almost entirely due to the Doppler-shifted back-scattered light. As a result, ODT signal-to-noise ratios (SNR) are substantially higher. Inasmuch as tomographic images of blood flow and tissue structure can be obtained simultaneously from a single scan, ODT has shown advantages over existing methodologies. The rationale for using ODT to characterize the underlying microvasculature is that the technique would be able to probe user-specified discrete spatial locations with high spatial resolution. High spatial resolution, noninvasive techniques for *in vivo* blood flow imaging are currently not available as a diagnostic tool in clinical medicine. Such techniques should have a significant impact for biomedical research and clinical diagnosis. The purpose of our study is to assess a noninvasive tomographic imaging technique with high spatial resolution (2–15 μm) to characterize and monitor fluid flow in highly scattering laser thermal injury tissues at user-specified discrete locations.

Methods

The ideal microvascular imaging techniques fulfill several requirements: a) probe the underlying microcirculation at a user-specified depth in both superficial and deep layers; b) distinguish arterial from venous flow; c) detect rapid blood flow changes; d) be safe, noninvasive; and e) produce reliable, and reproducible results. In our study, a high speed ODT based on spectral interferometry is used. The ODT instrument uses a fiber-optic Michelson interferometer with a super luminescent diode (SLD) ($\lambda_0 = 850$ nm, $\Delta\lambda_{FWHM} = 25$ nm) as the light source [14]. The sample and reference mirrors constitute the two arms of the interferometer. Light from the SLD and an aiming beam (He–Ne laser, $\lambda = 633$ nm) are coupled into a fiber interferometer using a 2 × 1 coupler and then split equally into reference and target arms of the interferometer by a 2 × 2 fiber coupler. Piezoelectric cylinders are used to modulate the optical path length of light in the reference and target arms by stretching the fiber wrapped around the cylinders. A ramp electrical wave (80 Hz) is used to drive the piezoelectric cylinders to generate optical phase modulation for the interference fringes ($f_o = 1600$ Hz). Light in the sample path is focused onto the turbid sample by a gradient index lens (NA = 0.2) with the optical axis oriented at 15° from the surface. ODT structural and velocity images are obtained by sequential lateral scans of the sample probe (i.e., fiber tip and gradient index lens) at constant horizontal velocity (800 μm/s) followed by a linear incremental movement along the surface.

Light, backscattered from the target, is coupled back into the fiber and forms interference fringes at the photodetector. Temporal interference fringe intensity ($\Gamma_{ODT}(\tau, t)$) is measured by a single element silicon photovoltaic detector, where τ is the time delay between light from the reference and target arms and is related to the optical path length difference (Δ) between the two by $\tau = \Delta/c$. High axial spatial resolution is possible because interference is observed only when τ is within the source coherence time τ_c, or equivalently, when Δ is within the source coherence length ($L_c = \tau_c c$). The interference fringe signal is amplified, high passed, digitized (20 kHz) with a 16-bit analog-to-digital (A/D) converter, and transferred to a computer workstation for data processing [Fig. 1].

The degree of damage is determined by two factors: the temperature and the time period for which the temperature is sustained. A non-linear relationship can exist between the two factors, and thus, even at a lower temperature but with prolonged exposure, thermal damage can still occur. A SurgiLase XJ150 carbon dioxide (CO_2) laser (Sharplan, NJ, USA)