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Application of infrared focal plane arrays for temperature monitoring in laser surgery

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ABSTRACT

Preliminary analysis of the applicability of IR FPAs to monitor temperature changes during various laser therapies has been performed at the Beckman Laser Institute. Temperature measurements of have been made implementing a high frame rate staring FPA. Extensive measurement skin surface temperature during pulsed laser exposure of port wine stain (PWS) were performed. Cursory experiments were performed on lung, teeth, and eye tissue during laser exposure.

1. INTRODUCTION

Lasers have been applied in medicine since their invention. In the early 1960's, medical researchers quickly implemented the advantages the laser presents as a unique light source. The first applications were in the treatment of retinal disease. Lasers are now applied in numerous medical tasks ranging from unclogging obstructed arteries, fracturing kidney stones, removing secondary cataracts and altering genetic material.

Many medical treatments implement laser energy to create controlled heat. In fact, the thermal effects created by the light's interaction with tissue are the most widely exploited phenomena associated with medical lasers. This heat results when the wavelength of the laser is matched closely with the absorption band of the target structure. This wavelength dependence, combined with the pulse duration control offered by medical lasers, offers researchers and practitioners a controlled heat source for numerous applications.

Imaging of heat caused by laser-tissue interaction in PWS is the primary motivation for experiments involving IR FPAs. Today, most laser tissue interactions occur on a controlled and short time scale. Thus, the high frame rates offered by FPA cameras allow time-dependent sequential imaging of the thermal events shortly following delivery of the laser pulse. Formerly, with only serial scan IR camera systems, fast events were impossible to image due to the inherently slow framing rates.

2. PORT WINE STAIN LASER THERAPY

PWS is a congenital, progressive vascular malformation of the dermis that occurs in an estimated 5 children per 1,000 live births. Although PWS may occur anywhere on the body, most lesions appear on the face and are noted to occur over the dermatome distribution of the first and second trigeminal nerves. PWS potentially results in considerable psychological and physical complications. Personality development is adversely influenced in virtually all patients by the negative reaction of others to a "marked" person. Detailed studies have documented these adverse psychological effects of PWS.

In early childhood, PWS are often faint pink markings on the skin. These markings tend to darken to red-purple, and by middle age, they often become raised as a result of the development of vascular papules or nodules, and, occasionally, tumors. Effects on underlying bone and soft tissue that occurs in approximately two-thirds of the patients with PWS further disfigures the facial features of many children.

Historical treatments for PWS included scalpel surgery, ionizing radiation, skin grafting, dermabrasion, cryosurgery, tattooing, and electrotherapy. Results from these therapies proved unsatisfactory due to the cosmetically unacceptable scarring

after treatment. More recent treatment options using the argon or flashlamp-pumped pulsed dye laser (FLPPDL) have offered a superior approach in therapy due to their ability to selectively destroy cutaneous blood vessels. Light passing through the epidermis is preferentially absorbed by hemoglobin (the major chromophore in blood) in the ectatic capillaries in the upper dermis. The radiant energy is converted to heat causing thermal damage and thrombosis in the targeted PWS vessels. Currently, only 10-20% of PWS patients obtain 100% fading of their marking even after multiple laser treatments.

The principal reason for these poor clinical results or treatment failure has been inadequate heat generation in large PWS blood vessels. In the ideal PWS, all vessels have a uniform diameter. Each of these vessels would then have a uniform thermal relaxation constant t_r . t_r is defined as the time required for the core temperature, produced by the absorbed light energy within the target blood vessel, to cool to one-half the original value immediately after the laser pulse. Ideally, the laser pulse duration (t_p) should closely match the vessel's thermal relaxation constant. If longer pulse durations are employed ($t_p > t_r$), heat diffuses outside the target structure, resulting in permanent scarring. Too short of a pulse results in a high-peak intravascular temperature rise which can produce explosive vaporization of tissue water, or photoacoustic transients which can result in vessel rupture. In most cases, the PWS vessels revascularize.

In the real world, vessel diameter varies greatly from patient to patient, and from site to site on the same patient. Improved therapeutic outcomes are expected should a method to determine t_r be developed. The relationship between vessel diameter and the vessel's thermal relaxation time has been determined, thus a method to determine the vessels diameter would aid in the selection of the correct pulse duration.

3. EXPERIMENTAL GOALS

Infrared tomography (IRT) implements the fast frame rate of an IR FPA to detect the time dependent temperature rise of a targeted tissue structure. IRT has been implemented in a number of materials science and non-destructive testing applications where defects or structures under the test object's surface are to be imaged. The use of IRT to image subsurface PWS blood vessels in human skin is novel.

For the purposes of IRT, PWS in human skin can be modeled as a plexus of subsurface absorbing structures. In this model, if a pulsed laser source is used to irradiate the skin, an immediate thermal wave can be detected on the skin surface due to laser-heated hemoglobin in the PWS blood vessels. The infrared emission from the skin surface degraded due to lateral diffusion. The motivation for using a high frame rate IR FPA is obvious since the image with least thermal diffusion will be integrated and observed immediately after the laser pulse.

Figure 1.
IR Emission from model PWS skin: a) immediately after laser exposure and b) some time later.

The broad objective of this research is the determination of the initial space-dependent temperature increase in the individual PWS blood vessels by a tomographic reconstruction algorithm, immediately following exposure to a diagnostic laser pulse, given only the recorded IR image sequence. Analysis of the time sequence of IR frames by lateral deconvolution and longitudinal inversion algorithms provides a means to determine directly the diameter and depth of individual PWS vessels. Given this information, the correct pulse duration of laser exposure can be selected, thus matching the thermal relaxation time of the PWS vessels, with predicted improvement in therapy.

4. EXPERIMENTAL

Using in vitro and in vivo model PWS systems, experiments have been conducted to test the performance of the IR imaging technique and its application to the lateral deconvolution and longitudinal inversion problems. In each experiment, a 0.45 ms pulsed laser source ($\lambda=585$ nm) was used to expose a test material containing subsurface absorbing structures that simulate PWS blood vessels. A compound IR lens imaged the surface increase in IR radiation from the test object onto a 128×128 InSb FPA.

Figure 2.
Schematic diagram of the IRT instrument used for preliminary experiments.

The FPA was operated at a frame rate of 217 Hz. The FPA pixels were digitized by two 2 MHz 12-bit A/D converters, and multiplexed into a single 4 MHz digital output. While the FPA was free running, the digital acquisition was triggered by a digital delay generator after the laser pulse. The digital data was acquired into fast RAM on a PC/AT computer, then transferred to a magnetic storage device for subsequent analysis. A diagram of the experimental configuration is offered in Figure 2.

5. RESULTS

Experimental data was collected at three different levels -- all of interest in PWS therapy. PWS models were manufactured using collagen films consisting of variable amounts of absorber to simulate individual PWS blood vessels in multilayered composite human skin. The PWS vessels are simulated by staining collagen films with an organic optically absorbing dye. The absorbance has been calibrated spectrophotometrically at the laser's wavelength to ensure heating. Phantom PWS vessels of varying thicknesses (125-175 μm wide) were layered under collagen films of varying thicknesses. Figure 3 is an IRT image captured of the phantom PWS, together with the resultant image after application of a lateral deconvolution algorithm.

Figures 4 and 5 are image sequences of a chick chorioallantoic membrane, and a PWS human subject, respectively. Easily visualized is the lateral thermal diffusion of the absorbing vessels.

Figure 4.
Sequence of IR images of chick chorioallantoic membrane.

Figure 5.
Sequence of IR images of human PWS.

6. FUTURE WORK

Future experiments are planned to confirm the applicability of the vessel deconvolution algorithms, and suitability of this technique for the determination of PWS vessel diameters. Subsequent work will include a novel laser which allows for adjustable pulse widths.

Also planned are additional experiments in dermatology, and novel experiments to test the applicability of IR FPA imaging in laser treatment in dentistry, ophthalmology, and a variety of other medical disciplines.

7. CONCLUSIONS

The IR FPA imaging system has been demonstrated as a reasonable tool for the acquisition of fast time sequences to monitor temperature during laser exposure. Further work needs to be performed to refine the applicability of this technology in medical laser therapies.

ADDITIONAL FIGURES

Figure 3.
IRT image of phantom PWS together with resultant image after lateral deconvolution algorithm.

8. REFERENCES

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