Optical technique for color imaging of temperature gradients in physiological media: a method to study thermal effects of cw and pulsed lasers

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Optical technique for color imaging of temperature gradients in physiological media: a method to study thermal effects of CW and Pulsed lasers

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ABSTRACT

Application of the thermocamera is limited to imaging surface temperatures at an air interface. We describe a technique which enables color imaging of temperature gradients inside optically transparent media. In an optical setup, very small changes in optical density of the media, induced by flow or temperature gradients, are color coded. Depending on the geometry of the temperature distribution, colors in the image can be related to absolute temperatures. The calibration is performed by making use of calculated temperature distributions of specific geometry and by thermocouple measurements.

This technique can be applied to study the thermal effects of cw and pulsed lasers during interaction with model and biological tissues. Using fast flash light photography or video imaging, temporal resolution in the microsecond region can be obtained. To study the feasibility of the technique, experiments were performed to image cw Nd:YAG and pulsed Holmium and Excimer laser light interaction with transparent gels and tissues submerged in saline. During the measurements, temperatures were also monitored using thermocouples on selected positions within the field of view.

At present, it is still difficult to translate the color images directly to absolute temperature images. The real time color images obtained with this color schlieren technique, however, provide a good understanding of thermo dynamics and thermal relaxation during laser tissue interaction with cw and pulsed lasers.

1. INTRODUCTION

During interaction of laser light with tissue, most of the photon energy is converted into thermal energy. The pathway along which this conversion takes place is dependent on the optical and thermal properties of the tissue and the (peak)power and the length of the laser pulse. In case of short high energy pulses, first shockwaves and microsecond vapor bubbles will be formed. Later, after extinction of the bubbles, thermal energy comes free and is dissipated. The distribution of the thermal energy in the tissue determines the local temperature rise. After laser exposure, it takes a particular time for the tissue to cool when the thermal energy is conducted over a larger tissue volume. This thermal relaxation time of tissues is an important parameter to obtain controlled tissue effects. Theoretically and experimentally, thermal relaxation times of all kinds of tissue are being evaluated [1,2]. These data will help to understand the mechanism of action (tissue effects) of the recently clinically introduced Holmium and Excimer lasers which are claimed to be 'cold' lasers compared to the continuous wave lasers like the Nd:YAG laser[3].

To study of the thermal interaction of pulsed lasers with tissue, there is a need to measure the temperature distribution in tissue with high spatial and temporal resolution. Presently, temperature measurements in medical laser research are performed using either thermocamera techniques or thermocouples. Thermocouples have to be applied invasively and show only the temperature at one position (1-D). Due to the dimension of the sensor itself the spatial resolution is limited to 0.1 mm and the temporal resolution to 10 ms. A thermocamera is able to provide the temperature distribution at a surface plane (2-D) but only at an air interface. The spatial resolution is limited to 0.1 mm and its temporal resolution is limited to 20 ms [4].

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In this paper the feasibility and application of an optical method will be discussed to visualize temperature distributions in model tissues with high spatial and temporal resolution. This method can be used to study the thermal effects of cw and pulsed lasers during interaction with biological tissues.

2. THEORY SCHLIEREN METHOD

Schlieren Method is an optical method to visualize density changes in media based on spatial filtering resulting in an enormous contrast enhancement[5]. The methods is used in a broad range of applications such as fluid dynamics, ballistics, aerodynamics and ultrasonic wave analysis image processing. The application discussed in this paper is aimed at temperature distributions.
The setup for the schlieren method consist of a so called optical processor and is shown in figure 1.

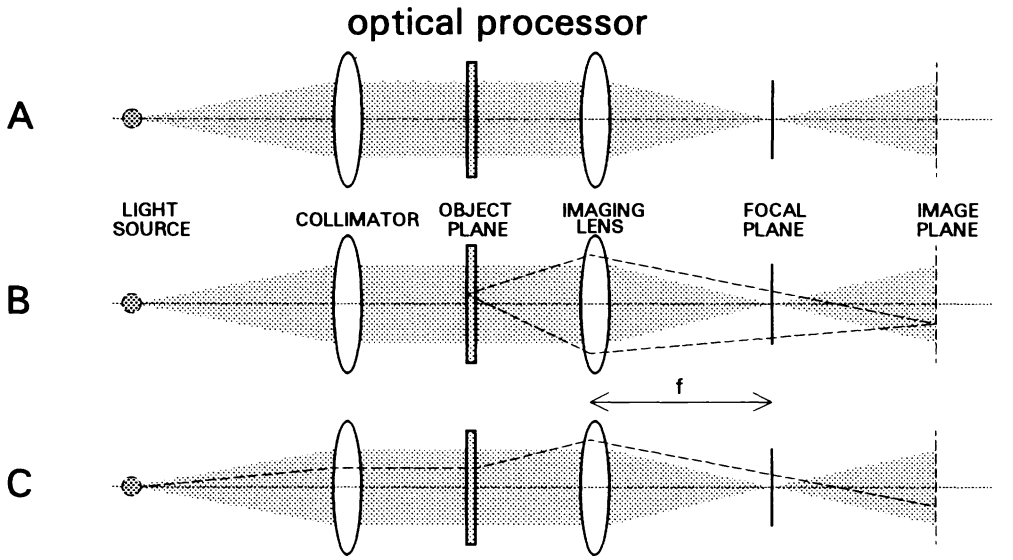

Figure 1: Setup optical processor

(A) From a light source, a parallel beam is created by positioning the source in the focal point of a collimator. This source can either be a laser whose beam is expanded or, in this case, white light emitted from a very small point source. A position between the collimator and imaging lens can be used as object plane where interaction with an object takes place. The imaging lens will focus the parallel beam in its focal point on the optical axis (when using monochromatic laser light, the fourier transform of the object, representing the spatial frequency spectrum of the object, is formed in the focal plane).
(B) The imaging lens will produce an image of the object at the image plane. This plane is located at the position prescribed by the lens formula: 1/focal length = 1/object distance + 1/image distance [6]
(C) Due to variations in the refraction index or irregularities in the medium in the object plane, some rays of the parallel beam will be deflected and they will cross the focal plane at a particular distance d from the optical axis. Non distorted rays will be focused on the optical axis.

By inserting a mask or a filter in the focal plane of the imaging lens (figure 2), it is possible to block out the non deflected rays, preventing them to reach the image plane or, to earmark rays crossing the plane at certain positions. This process of modifying the object information in the focal or transform plane is known as spatial filtering. By blocking the rays crossing the optical axis, only refracted and diffracted rays will pass the transform plane and form an image at the image plane. This results in an enormous contrast enhancement of the image due to the subtraction of the background light.

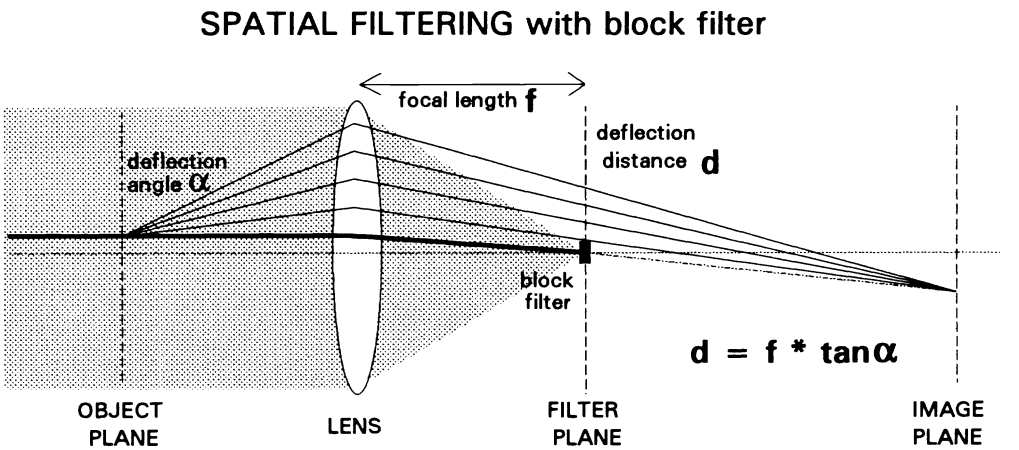

Figure 2: Schlieren setup with block filter

The result of such filtering is shown in figure 3. Using a block filter, a image is obtained from all the deflected light but it does not contain information on the degree of deflection.

Figure 3: Effect of spatial filtering using a block filter. Left: normal view of turbulent hot water in front of a fiber after exposure to a holmium laser pulse. Right: after subtraction of background light the heated environment becomes clearly visible

3. COLOR SCHLIEREN METHOD

Depending on the deflection angle α and the focal length of the transform lens, a ray will pass the filter plane at a deflection distance d from the optical axis (figure 2):

$$d = f * \tan \alpha$$

The information on the degree of deflection can be preserved by color coding the rays[7] coming through the filter plane using a rainbow filter (figure 4) [8]. This filter consists of concentric rings in a continuous color band similar to the white light spectrum. The center of the filter is a black dot blocking the background light. Adjacent to the black dot, going away from the center, the colors shift gradually from blue to red. Rays passing the filter plane will be color coded depending on the deflection distance d and will be reconstructed to an image at the image plane. The generated color image will show position dependent the degree of deflection in the object plane. From the color, the deflection angle α can de determined which is related to the variation in the refractive index of the mediumin the object plane.

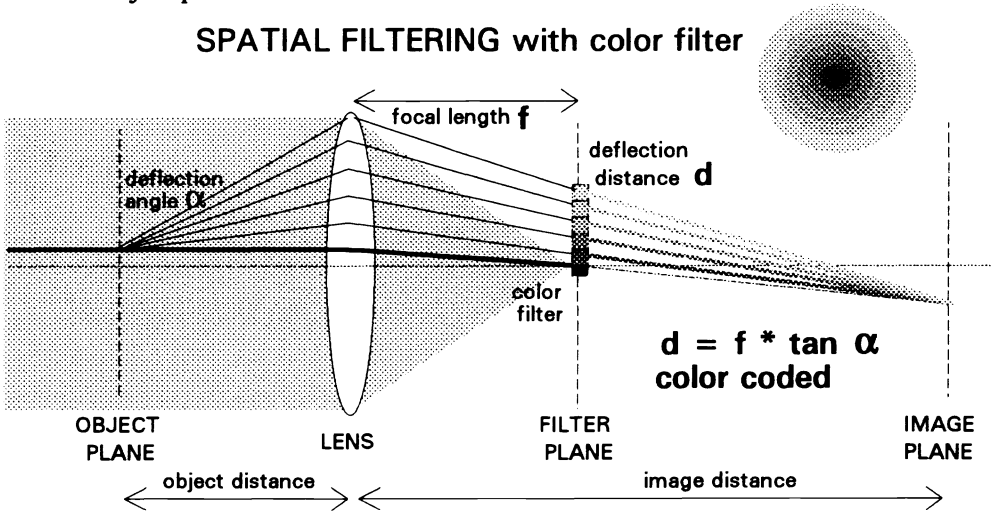

Figure 4
Color schlieren setup with rainbow filter

In figure 5 the effect of the color schlieren is shown in comparison to a image obtain using a normal block filter.

Figure 5: Effect of the color schlieren setup. Left: 'normal' schlieren view of fiber on top of a tissue slab surrounded by heated water (white area). Right: color schlieren view, the colored areas, represented by distinct gray levels in this black-and-white reproduction, show the temperature distribution in the water around the laser irradiated tissue slab.

4. DEFLECTION OF RAYS BY A MEDIUM

Rays can be deflected in a transparent medium due to variation in the refraction index. This variation results from:

a) Inhomogeneity of the medium: The medium might be a mixture of more compounds with a different density or a liquid with a solvent which is not uniformly distributed.

b) Local stresses can be induced by shockwaves travelling through the medium changing the local density. In transparent solids, external forces will induce local density variation in the structure of the material.

c) A medium usually expands due to a temperature increase so the density decreases and hence the refractive index. In biological tissues, the basic medium is water which will act as the optically active medium.

For this study, the deflection of rays due to the variation in the refractive index of water [9] is used to visualize temperature gradients in tissues. Figure 6 shows the relation between temperature and the refractive index of water. The refractive index decreases with increasing water temperature.

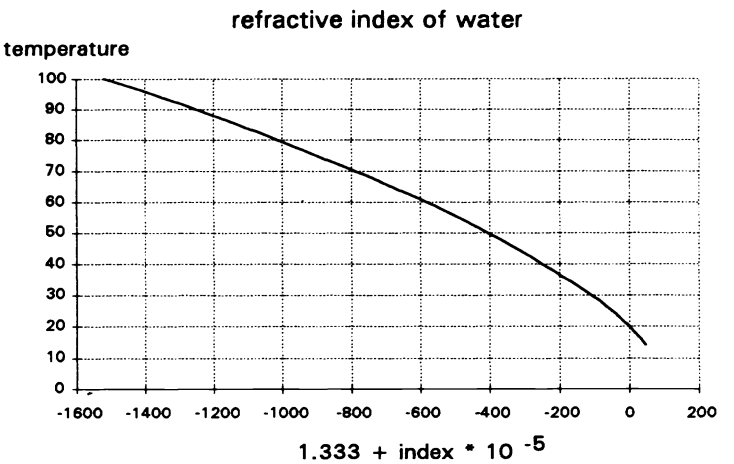

Figure 6
Refractive index of water in relation to temperature

5. RAINBOW SCHLIEREN SETUP

To study the thermal interaction of cw and pulsed laser systems with biological tissues a rainbow schlieren setup was used as illustrated in figure 7

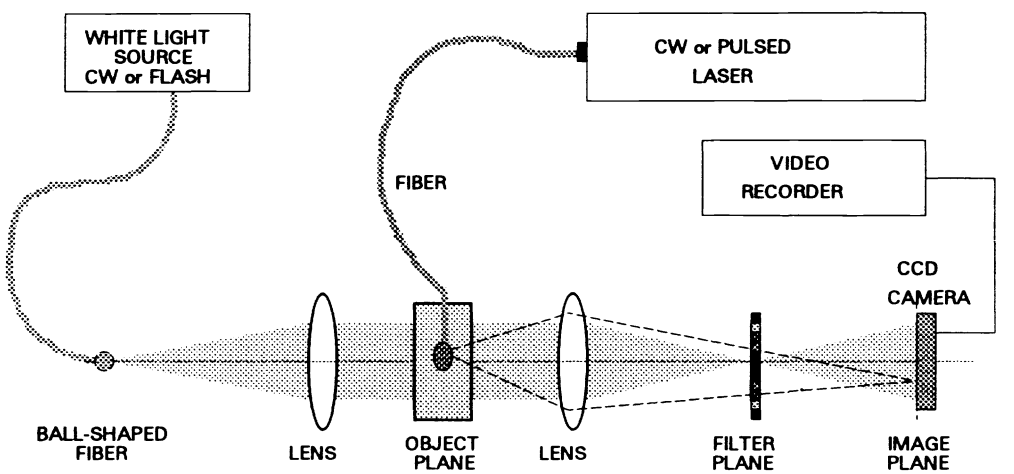

Figure 7: Rainbow schlieren setup to study laser tissue-interaction

A white light source is coupled into a ball-shaped fiber. The light emitted from the fiber is focused due to the spherical fiber end and subsequently divergences. The focal point of the collimating lens coincides with the focus of the fiber. The diameter of the lens is matched with the divergence of the beam so all light is collimated. A rectangular tank filled with water is positioned in the object plane. The walls are perpendicular to the parallel beam to prevent any optical distortion due to refraction. A fiber with or without probe is submerged in the water along with tissue or model tissue within the field of view. The position of the imaging lens, the filter and the CCD camera are chosen depending on the magnification desired according to the lens formula. The filter is positioned in the focal plane of the imaging lens. The diameter of the filter determines the dynamical range of temperatures that can be visualized. Using a x-y microtranslator, the filter can be optimally aligned on the optical axis. The CCD camera is positioned in the image plane. Additional filters can be used to filter out scattered light from the primary laser wavelength. To obtain microsecond resolution, a video camera with high speed mode can be used.

6. CALIBRATION OF SETUP

To interpret the color image as a temperature image, the relation between color and temperature should be calibrated. There is a direct relation between the deflection distance d and the color depending on the size of the filter. The relation of the deflection distance and the temperature : $d = f(t)$ depends on:
1) the angle of deflection α, 2) the focal length of imaging lens, 3) the object distance, 4) the image distance, and 5) the symmetry of the refractive index distribution.
The symmetry of the refractive index distribution is of major importance. This calibration can only be performed by assuming a particular symmmetry. One can approximate the distributions by an unidirectional or an axially symmetrical distribution.

6.1 Uni-directional refractive index distribution

This situation occurs in case of a temperature gradient above a heated surface (figure 8) and can be considered a 1 - D situation. An example of the calibration curve for an uni-directional temperature distribution is given in figure 9.

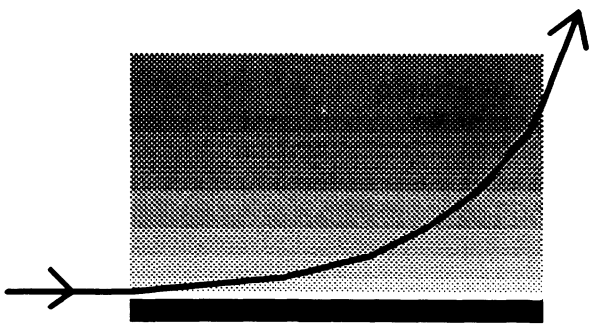

Figure 8: Deflection of ray in medium with a temperature gradient above a hot surface

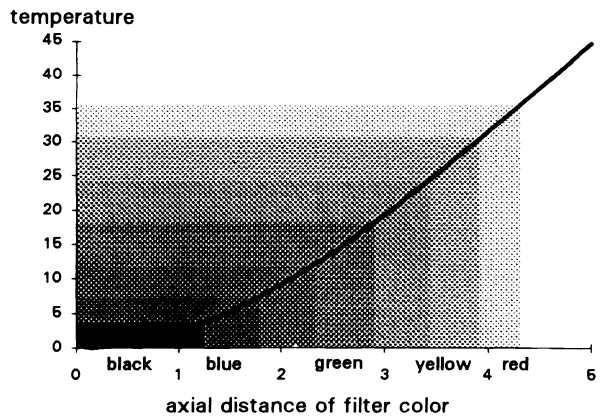

Figure 9: Relation between color and temperature in color image of temperature distribution

6.2 Axially symmetric refractive index distribution

This situation occures in case of a temperature gradient around a 'hot spot' in a cylindrical or spherical geometry and can be considered a 2-D situation.

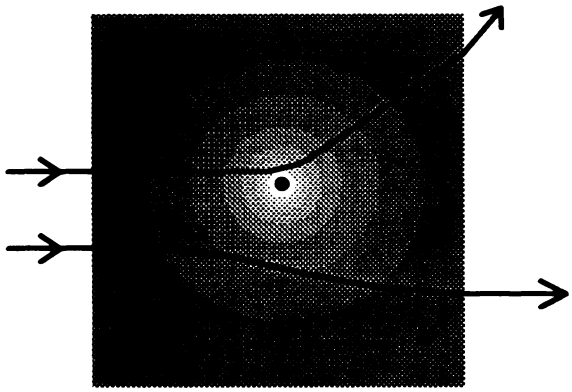

Figure 10: Deflection of rays in medium with a radial temperature gradient

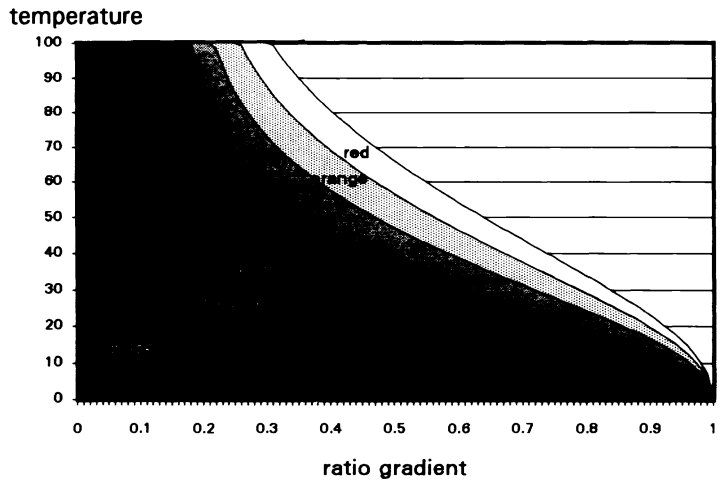

Figure 11:Relation between color and temperature in color image of temperature distribution

An example of the calibration curve for an axially symmetric temperature distribution is given is figure 11. This graph is difficult to interpret. The temperature at a particular position in an image has to be determined from the color and the ratio of the temperature gradient. This ratio is the distance from the axis of symmetry (usually the highest temperature) divided by the distance over which the temperature gradient extends (from the axis of symmetry to ambient temperature (black)).

7. APPLICATIONS

The modified schlieren setup can be used for a broad range of experiments related to thermal imaging and modelling. Depending on the time resolution required, a pulsed or a cw light source may be used. A practical problem might be the efficient coupling of a white light source into a fiber to have sufficient light for imaging.

7.1 Time resolved studies for pulsed lasers

7.1.1 Ultra fast setup

To capture ultra fast phenomena like shockwaves[10], bubbles[11] and the start of heat diffusion, the pulse duration of the light source should be in the nanosecond region. Using an arc lamp, pulses of 100 ns are obtained but it is questionable if the light is sufficient for imaging. A pulsed laser, e.g. a copper vapor laser with 10 ns pulses, can be preferred though it is not possible to color code the image since the light source is monochromatic. Still, it is possible to produce temperature resolved images using special design spatial filters or using a multiple wavelength laser, a broadband dye lasers or laser induced fluorescence light.

The high temporal resolution can be used to study the thermal relaxation of small structures (μm region). Being able to image the very beginning of heat diffusion, it might be determined if particular processes like bubble expansion and implosion are adiabatic processes.

Practical problems might be the triggering of the laser source and dealing with multiple exposures using a high repetition rate laser.

7.1.2 Fast color setup

Colored images representing temperature gradients with high temporal resolution can be obtained using flashlights which generally produce 1 - 100 μs white light flashes. The microsecond region is interesting to study vapor bubbles dynamics and heat diffusion associated with pulsed laser interaction with tissue. Sufficient imaging light might be a problem. Also the repetition frequency of the flashlight is limited and might be a trade-off with light intensity per pulse.

7.1.3 Slow (continuous) color setup

To study the heat diffusion in a large volume of tissue a continuous white light source e.g. a xenon lamp can be used. The time resolution will be determined by the frame rate of the video camera (1 ms to 40 ms) which is sufficient to study tissue interaction with continuous wave lasers. Heat diffusion can be studied continuously and the data can be verified with thermocouple measurements which have the same order of temporal resolution.

7.2 (Model) tissue in object plane

Figure 12 shows the object plane in detail. An absorbing layer or tissue slab is positioned in the center of the field of view with it surface parallel to the path of the rays. This way the slab produces the smallest shadow in the image plane. In the absorbing slab the light-tissue interaction takes place. The thickness of the absorbing slab is matched with the penetration depth of the laser wavelength which is studied. The original heat source is in the absorbing slab. From here the thermal energy is conducted to the environment. This environment is transparent to allow the white light rays to pass while interacting with the medium. The slab is irradiated with laser light coming from a fiber perpendicular to the surface so from the top in the image.

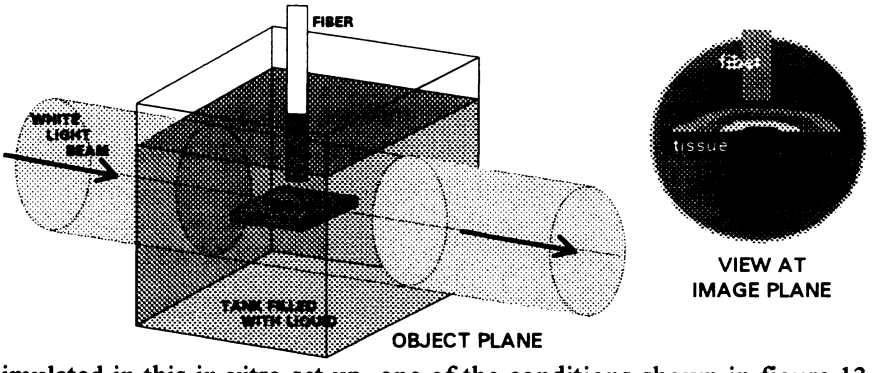

Figure 12
Detailed graph of object plane with inset of field of view

Depending which in vivo situation is simulated in this in vitro set-up, one of the conditions shown in figure 13 is taken. The absorbing layer is either the medium itself or a slab of tissue acting as the heat source. Consequently, the heat is diffused into the medium or into a transparent model tissue with similar thermal properties as the tissue [12] to visualize temperature gradients. For the transparent tissue model either an agar gel or polyacrylamide gel can be used.

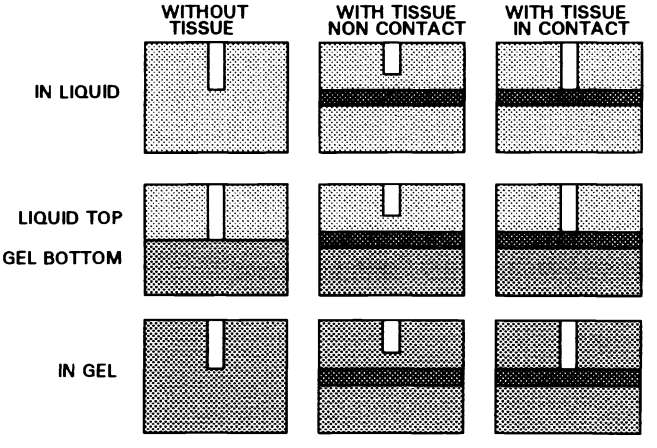

Figure 13:
Various conditions for temperature distribution study in (model) tissues

The wavelength of the laser studied might be absorbed directly by the medium or by the gel. It is also possible to disolve an absorber in the medium as long as the absorber does not influence the transmission of visual light. These conditions are depicted in the first column in figure 13. To simulate the in vivo situation as close as possible a slab of the original tissue is used for the absorption and scattering events. This can be performed with the medium in between or direct in contact with the fiber (figure 13, the second and third column, respectively). The gel is to replace the tissue structure. In tissue or gel the heat transfer can only take place by heat conduction. In a liquid environment, on the other hand, also convection is involved which is a very effective way to transfer heat. So for some applications there is a liquid tissue/gel boundery (figure 13, second row). To simulate interstitial applications the fiber is totally embedded in the gel (figure 13, lower row).

7.3 Thermocouple measurements

Simultaneous with the schlieren photography, thermocouples are present in the image field to provide absolute temperature measurements of local positions from which relative temperatures can be derived using the color schlieren images. The temporal resolution of the thermocouples can be down to 1 ms.

8. EXPERIMENTS

To study the feasibility of the setup, initial experiments were performed on laser-tissue interaction with a cw 1064 nm Nd:YAG, a 308 nm, 120 ns Excimer laser and a 2.1 μm, 250 μs Holmium:YAG laser. Either water with or without an absorbing solvent, gel or porcine aortic tissue was used as medium. Laser light was transported using 300 and 600 μm fibers. Images were recorded on video later transformed to a hardcopy for evaluation. Temperature measurements using thermocouples were recorded by computer and correlated with the video recordings.

9. RESULTS

Figures 14 and 15 provide some examples of color schlieren images obtained. The objective of this paper is just to describe the color schlieren method as applied in the biomedical field. The results will be published in more detail elsewere [13]. Unfortunately, the temperature information in the figures is largely lost in the black-and-white reproduction.

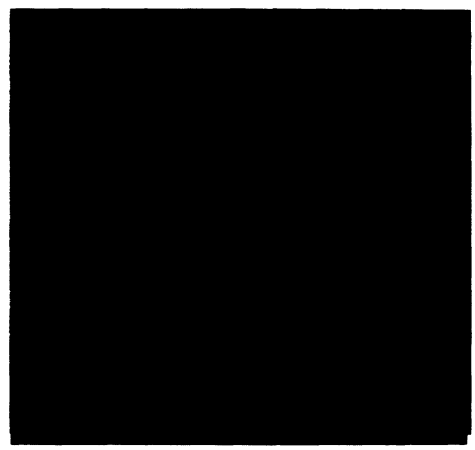

Figure 14: Temperature distribution around a 1 mm thick slab of aorta between gel layers after 10 s, 15 W exposure with cw Nd:YAG. Note the transfer of heat below the aortic tissue.

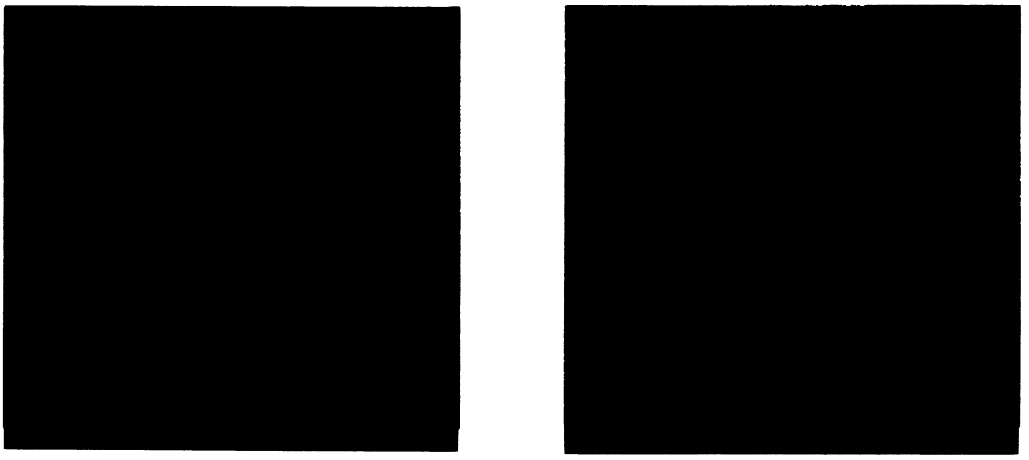

Figure 15: Multiple 300 mJ Holmium laser pulses from a 300 μm fiber at 5 Hz in gel. Left: temperature distribution after first pulse. Right: After 10 pulses the total environment is heated since the repetition rate of the pulses is higher then the thermal relaxation time of the gel.

10. DISCUSSION

The color schlieren method provides relative information as to temperature distributions and thermal relaxation. At first instance, the dynamic images provides insight in the mechanism of laser-tissue interaction. A fundamental challenge is the color-temperature calibration.

10.1 Image quality (resolution)

The quality of the images depends on all individual components.

10.1.1 Filter

The color filter should have a gradual rainbow like distribution of as many colors as possible. The filter can be made on photographic film from a spectrum of a white light source [5] or it can be computer generated. Especially the diameter of the filter is important for the range of temperatures and the spacial resolution that can be obtained. A filter of only a few mm diameter is difficult to manufacture.

10.1.2 White light source

To have sufficient light for imaging, the light has to be coupled efficiently into the illumination fiber. A ball-shaped fiber provides a good point source. As a alternative a pin-hole could be used. The intensity at the image plane depends on the magnification. The higher the magnification, the lower the intensity. Most practical for high temporal resolution is a flashlight with a pulse length of tens of microseconds. For shorter pulses, the intensity will be problematic.

10.1.3 Optics

To obtain high spatial resolution in the filter plane, high quality, color abberation corrected lenses are needed. The diameter of the lens should be at least the diameter of the view of interest in the object plane. In this study this diameter could be varied between 3 to 50 mm.

10.2 Color - temperature calibration

In order to be able to relate the colors to temperature, a symmetrical temperature distribution is necessary with a presumed geometry which is either planar, cylindrical or spherical. For most conditions, the geometry can be approximated by one of these geometries. The heat source is usually a point or a disk. Also the direction of the heat conduction is either uni-directional or radial. Convections associated with turbulence can not be related to absolute temperatures, although the images provide a good view of the mechanism of thermal transport.

The theoretical relation of color and temperature was checked by measuring temperature with thermocouples in a setup with well defined geometry. The color images showed the position of the thermocouple and the color of the surrounding which should reflect the absolute temperature of the thermocouple reading. The thermocouple data showed a safisfying agreement with the temperatures determined from the color images.
For each magnification and color filter, the set-up has to be recalibrated and calibration graphs similar to figures 9 and 11 have to be plotted. During expriments it is sensible to have a few thermocouples recording temperatures within your field of view for confirmation and backup. For many applications the images recorded already are useful without absolute temperature determination.

10.3 Model tissues

For the basic laser-tissue interaction there is no suitable model-tissue. Especially scattering events are difficult to simulate in model tissues. So real tissue is used with a mininal volume limited to the effective penetration depth for the wavelength studied. If absorption is high and dominates scattering, one can use an absorber solved in the model tissue as long as it is transparent for the visual range of wavelength. There is such an absorber for the UV, but we are still looking for such an absorber for the near infrared.

11. CONCLUSIONS

The color schlieren methods can be used to visualize temperature distributions in model tissues with high spatial and temporal resolution. This method is a useful tool to study especially the thermal effects of cw and pulsed lasers during interaction with biological tissues.
At present , it is still difficult to translate the color schlieren images to absolute temperature images. However, the real time color images provide a good understanding of thermo dynamics and thermal relaxation during laser-tissue interaction with cw and pulsed lasers.

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