Imaging laser-induced thermal fields and effects

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ABSTRACT
Laser light interaction with biological tissues is a combination of optical, thermal and mechanical effects depending on the energy applied per unit of volume per unit of time. Visualization of the phenomena with a high temporal and spatial resolution, contributes to a better understanding of the mechanism of action, especially when pulsed lasers are involved. For this goal, setups were developed based on Schlieren techniques to image the interaction of pulsed (CO₂, Holmium and Excimer) and CW (CO₂, Nd:YAG, Cu-vapor) lasers with physiological media and biological tissues. In a ‘fast’ Schlieren setup, images of shock waves and fast expanding and imploding vapor bubbles were captured using very short light flashes (10 ns -10 μs). These recordings suggest that these explosive vapor bubbles seem to be the main dynamism for tissue ablation. In a ‘color’ Schlieren setup, very small changes in optical density of the media induced by temperature gradients, were color coded. Calibration of the color images to absolute temperatures were performed by using calculated temperature distributions and by thermocouple measurements. Cameras with high speed shutters (0.1 - 50 ms) enabled the recording of dynamic images of the thermal relaxation and heat diffusion in tissues during variation of pulse length and repetition rate. Despite pulse lengths < ms, heat generation in tissue was considerable already at pulse repetition rates above a few Hz. Similar Schlieren techniques were applied to study the thermal characteristics of laser probes, e.g. for the treatment of Benign Prostatic Hyperplasia (BPH). In combination with thermal modeling an optimal therapy might be predicted. Schlieren techniques, generating high-speed and ‘thermal’ images, can provide a good understanding of the ablation mechanism and the thermo-dynamics during laser-tissue interaction with continuous wave and pulsed lasers.

1. INTRODUCTION
To study of the thermal interaction of pulsed lasers with tissue, temperature measurements are usually performed using either thermocamera techniques or thermocouples. Both these methods have limitations as to resolution or interference with the medium of interest 1. As an alternative the author introduced two years ago, a technique which enables color imaging of temperature gradients inside optically transparent media 2. In an optical setup, very small changes in optical density of the media, induced by temperature gradients or local stresses, are color coded. This method, based on Schlieren techniques, has been be applied to study the thermal and mechanical effects of continuous wave (CW) and pulsed lasers with a high temporal and spatial resolution during interaction with model and biological tissues. Visualization of these phenomena, contributes to a better understanding of the mechanism of action, especially when pulsed lasers are involved 3. This paper gives an overview of potential applications.
2. SCHLIEREN TECHNIQUES

2.1 Optical setup

In figure 1 the optical setup, based on Schlieren techniques, is illustrated.

![Schlieren setup to study laser tissue-interaction](image)

A monochromatic (laser) or 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 divergences subsequently. The focal point of a 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 between the collimator and imaging lens, the ‘object’ plane. The walls are perpendicular to the parallel beam to prevent any optical distortion due to refraction. Within this tank conditions are created to study laser tissue interaction. The imaging lens will focus the parallel beam in its focal point on the optical axis. However, rays can be deflected due to variations in the refraction index or irregularities in the medium in the object plane induced by local stresses or temperature gradients. These rays will cross the focal plane at a particular distance $d$ from the optical axis (figure 2). The 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, 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 filter plane is known as spatial filtering. By blocking the rays crossing the optical axis, only refracted and diffracted rays will pass the filter 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.

![Spatial filtering with block filter](image)

$d = f \times \tan \alpha$
Depending on the deflection angle \( \alpha \) 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): 
\[
d = f \cdot \tan \alpha
\]
The information on the degree of deflection can be preserved by color coding the rays coming through the filter plane using a color filter (fig. 4). This filter consists of concentric rings of discrete color bands separated by small black rings. 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 each color, the deflection angle \( \alpha \) can be determined which is related to the variation in the refractive index of the medium in the object plane. The color image can be interpreted as a thermal image when the relation between refractive index and temperature gradient is known. The black rings in the filter (fig. 4) will result in black lines in the image separating the discrete colors giving an impression of ‘isotherms’.

![SPATIAL FILTERING with color filter](image)

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 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.

![Figure 4 Example of color filter](image)

### 2.2 (Model) tissue in object plane
Depending which in vivo situation is simulated in this in vitro set-up, one of the conditions shown in figure 4 is taken. A medium or layer of tissue is exposed directly by a laser beam or indirectly through an optical fiber. The medium itself or a slab of tissue will absorb the laser light. Consequently, heat is generated and will diffuse through the medium or transparent model tissue. A transparent polyacrylamide gel which has similar thermal properties as the tissue is used as tissue model to visualize the temperature gradients.
The wavelength of the laser studied might be absorbed directly by the medium or by the gel. It is also possible to dissolve an absorbing dye 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 5. To simulate the in vivo situation as close as possible a slab of the original tissue is used for the absorption and scattering events (fig.5, the second column). In tissue or gel the heat transfer can only take place by heat conduction. In case of a liquid environment, also convection is involved which is a very effective way to transfer heat. An air environment, on the other hand, will act as a perfect isolator (fig.5 second row). To simulate interstitial applications a fiber is totally embedded in the gel (fig.5, lower row).

### 3. 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 $\alpha$, 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 symmetry. One can approximate the distributions by an unidirectional or an axially symmetrical distribution.

#### 3.1 Uni-directional refractive index distribution

This situation occurs in case of a temperature gradient above a heated surface (figure 6) and can be considered a 1-D situation. An example of the calibration curve for an uni-directional temperature distribution is given in figure 7.

![Figure 6: Deflection of ray in medium with a temperature gradient above a hot surface](image)

![Figure 7: Relation between color and temperature in color image of temperature distribution](image)
3.2 Axially symmetric refractive index distribution
This situation occurs 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 8: Deflection of rays in medium with a radial temperature gradient](image8)

Figure 8: Deflection of rays in medium with a radial temperature gradient

![Figure 9: Relation between color and temperature in color image with a radial temperature distribution](image9)

Figure 9: Relation between color and temperature in color image with a radial temperature distribution

An example of the calibration curve for an axially symmetric temperature distribution is given in figure 9. 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)).

3.3 Calibration measurements
Unidirectional and cylindrical temperature gradients were created by heat dissipation from an electrical current through carbon plates and rods (0.5 - 3.0 mm diameter) in an aqueous medium while imaged with the color Schlieren method. The absolute temperatures were determined by scanning a 0.1 mm diameter thermocouple through the gradient and the results were compared to theoretical expected values. There was a good fit between data and theory for the unidirectional gradient. For the cylindrical gradient, the fit depended on the orientation (vertical or horizontal) of the carbon rods due to convection. For a larger diameter of the rod, the cylindrical temperature gradient resembles the unidirectional gradient.

![Figure 10: Calibration measurements for a plate and rods with various diameters compared to the theoretical curve](image10)

Figure 10: Calibration measurements for a plate and rods with various diameters compared to the theoretical curve
3.4 Thermocouple measurements
Simultaneous with the schlieren imaging, thermocouples are present in the image field to provide absolute temperature measurements of local positions from which absolute temperatures can be derived using the color schlieren images. The temporal resolution of the thermocouples are down to 1 ms.

4. APPLICATIONS I: TIME RESOLVED STUDIES FOR PULSED LASERS
The schlieren setup can be used for a broad range of experiments related to imaging and modelling. Depending on the time resolution required, a pulsed or a cw light source is be used.

4.1 Ultra fast setup: Shock-wave imaging
To capture ultra fast phenomena like shockwaves, explosive bubbles 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. 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 should be possible to quantify the degree of deflection due to the shock or stress wave in the medium by using special design spatial filters or using a multiple wavelength laser, a broadband dye laser or laser induced fluorescence light.
Having control over the synchronization between flashlight and pulsed laser, it is possible to obtain quantitative data on the speed of shockwaves. The high temporal resolution can be applied to study the thermal relaxation of small structures (μm region). Being able to image the very beginning of heat diffusion, it might be possible to determine if particular processes like bubble expansion and implosion are adiabatic processes.
This fast setup was used to study shockwaves induced by Excimer and Holmium laser interaction in water. For the 308 nm excimer laser light an absorbing dye was added to the water. The 2.1 μm holmium light was absorbed by the water itself. The water was exposed to the laser light which was delivered through a fiber. Shock wave were observed at the beginning of expansion of an explosive vapor bubble and at the moment of implosion. Figure 11 b shows the shock wave at the implosion of a holmium vapor bubble.

![pulsed laser induced shock waves](image)

Figure 11 a) scheme of shock wave imaging setup

b) shock wave at implosion of Holmium bubble
4.2 Dynamics of vapor bubble expansion and implosion
Making use of the 10 kHz repetition frequency the Copper-vapor laser, it is possible to make multiple exposure images. During the 1 ms exposure time of one image, the laser has flashed 10 pulses of 10 ns each 100 μs apart. This results in a superposition of 10 still-frames of a dynamic process like bubble expansion at a water surface during exposure with a 350 μs Holmium pulse as shown in figure 12.

Figure 12: a) scheme of bubble imaging setup b) 7 contours of expanding bubble each 100 μs apart

4.3 Explosive bubble expansion and implosion
Images with high temporal resolution can be obtained using flashlights which generally produce 1 - 10 μs white light flashes. The microsecond region is interesting to study vapor bubbles dynamics and heat diffusion associated with pulsed laser interaction with tissue. The intensity and the repetition frequency of the flashlight is usually limited. Explosive bubbles can be studied using the Schlieren technique (fig.13b) but also using direct white light illumination (fig.13c).

Figure 13:
a) scheme of bubble imaging setup b) ‘Schlieren’ bubble image c) ‘normal’ flash light image
5. APPLICATIONS II: COLOR IMAGING OF ‘SLOW’ THERMAL EFFECTS

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 exposure time for one frame of the video camera (1 ms to 40 ms) which is sufficient to study thermal relaxation times and heat diffusion during pulsed and cw laser interaction with tissue. The data can be verified with thermocouple measurements which have the same order of temporal resolution.

5.1 Thermal effects of pulsed lasers

After implosion of a bubble which has been created by a pulsed laser, the latent heat of vaporization is dissipated in the environment. Especially when laser pulses are delivered at a frequency higher then 3 Hz. the heat dissipation will be too slow for relaxation resulting in a temperature rise of the tissue. These thermal effects can be perfectly visualized using the color Schlieren technique. Figure 14 shows the temperature distribution in a gel created after 5 Holmium pulses of 500 mJ at 5 Hz. Although the original colored image is represented here in black and white, the temperature distribution is well delineated by the black lines acting as ‘isotherms’.

Figure 14:

a) Scheme of thermal effects of Holmium laser

b) the temperature distribution in a gel created after 5 Holmium pulses of 1 J at 5 Hz

The various parameter involved with pulsed laser interaction with tissue like pulse energy, pulse repetition rate and pulse length can be studied in relation to the thermal effects. This is being applied for continuous wave and pulsed CO₂ lasers. The ablation threshold can be easily determined using this imaging technique. Also the thermal damage around the ablation crater can be visualized (fig.15b).

Figure 15:

a) Scheme of thermal effects of CO₂ laser.

b) Image of temperature distribution along crater wall in gel
5.2 Port wine stain treatment modelling
For many years theoretical models are being computed to determine the optimal treatment for port-wine stains \(^9\). Two of the most important parameters are the thermal relaxation time of the blood vessels and the pulse time of the laser. The color schlieren technique makes it possible to verify these calculations by measuring the relaxation time in relation to vessel diameter and laser pulse. Initial experiments were performed using thin metal wires embedded in the gel model. Thermal relaxation of the artificial vessels were imaged either in side view (fig. 16b) or along the axis of the vessel (fig. 16c).

Figure 16:  
a) Scheme of vessel model  
b) Image of heated vessels, axial view  
c) Image of heated vessel, side view

5.3 BPH treatment modelling
The treatment of Benigne Prostate Hyperplasia (BPH) using laser has become popular in the last few years. Many side firing devices and treatment modalities have been introduced \(^10\). Still, the optimal dosimetry for each of these devices has to be determined. Thermal imaging of the temperature distribution in a tissue model for the prostate might be helpful. A gel model with an absorber for Nd:YAG laser light was developed to study the effect of power and exposure time on the heat distribution as shown in figure 17.

Figure 17:  
a) Scheme of prostate model  
b) Thermal image of temperature distribution in gel model

Nd:YAG prostate treatment (BPH)
5.4 Thermal evaluation of fiber tips
In view of the BPH treatment also the side firing fiber tips were evaluated as to their optical, thermal and mechanical properties. The laser beam emitted by these devices are also partly absorbed by the probes themselves resulting in substantial heating of the probe. This effect could again be studied using the color schlieren imaging method as illustrated in figure 18 for a device consisting of a metal mirror.

![Thermal imaging fiber tips](image)

Figure 18: a) Scheme of fiber tip imaging  

b) thermal image of side-firing fiber tip for BPH treatment

6. DISCUSSION

The color schlieren method described in this paper provides qualitative and for some conditions also quantitative information of temperature distributions, thermal relaxation and diffusion in tissue models. The dynamic imaging of phenomena provides a good understanding of the mechanism of laser-tissue interaction. The imaging are also useful for education and training of students, scientists and physicians.

6.1 Filter
The original color filter design was a gradual rainbow like distribution of as many colors as possible. However to introduce a better quantification, the more recent filter designs consist of discrete colors separated by black rings. In the image these black rings provide an impression of 'isotherms'. The filters are computer generated and photographed from the computer screen on slide film. The diameter of the filter is important for the range of temperatures and the spacial resolution that can be obtained.

6.2 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. The calibration measurements with thermocouples show an acceptable conformity with the theoretical curves for the unidirectional geometry (figure 10). Though, convections, sometime associated with turbulence, are of influence for the calibration. The axial geometry is more difficult to calibrate. If the diameter of the cylindrical or spherical heat source is larger then a few millimeters, the calibration measurements show that the calibration becomes similar to the uni-directional distribution.

It is impossible to calibrate turbulence. Still, the images provide a good insight in the mechanism of thermal transport.

For each magnification and color filter, the set-up has to be recalibrated and calibration graphs similar to figures 10 have to be plotted. During experiments it is sensible to have a few thermocouples recording temperatures within your field of view for absolute temperatures. For many applications, the images recorded already are useful without absolute temperature determination.
6.3 Model tissues
For the basic laser-tissue interaction there is no suitable model-tissue available that is also transparent. Especially scattering events are difficult to simulate in model tissues. Real tissue can be used with a minimum 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 wavelengths. Such absorbers are available both the UV and near IR (Nd:YAG).

7. 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. For symmetric temperature distributions, it is possible to translate the color schlieren images to absolute temperature images within an acceptable accuracy. The real time color images provide a good understanding of thermo dynamics and thermal relaxation during laser-tissue interaction with CW and pulsed lasers.

8. REFERENCES