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# Quantification and Localization Using Diffuse Photons in a Highly Scattering Medium

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SPIE PROCEEDINGS SERIES

**Volume 2082**

*Published by*
SPIE—The International Society for Optical Engineering

# Contents

# TIME-RESOLVED TRANSILLUMINATION OF TURBID MEDIA

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## ABSTRACT

The suitability and limits of time-resolved transillumination to determine inner details of biological tissues are investigated by phantom experiments. The achievable improvement will be demonstrated by using different phantoms (absorbing objects embedded in a turbid medium). By means of line-scans across a sharp edge the spatial resolution ($\Delta x$) and its dependence on temporal resolution ($\Delta t$) can be determined. To demonstrate the physical resolution according to the Rayleigh-criterion, measurements were performed on blackened bead pairs. Investigations with partially transparent beads demonstrate the high sensitivity of time-resolving techniques with respect to variations in scattering or absorption coefficients.

## 1. INTRODUCTION

The noninvasive diagnosis of tissue by light is of great interest for the examination of organs as well as for preventive or medical routines.[1,2] Due to the enormous multiple scattering of the light in the tissue, however, the spatial resolution is restricted. But it is possible to separate multiple scattered photons that only permit poor spatial resolution from less often scattered photons with better spatial resolution by means of a time-of-flight limitation. Systematic measurements were carried out on different phantoms (turbid media with inserted absorbers) to clarify in quantitative terms the benefit offered by a time-resolved transillumination technique. Not only phantoms with completely absorbing objects were examined, but also those with partially transparent ones. The optical tissue parameters (reduced scattering length $l_S'$, absorption length $l_A$) depend not only on the type of tissue but also on the optical wavelength used. Phantoms with reduced scattering length values of $l_S' = 0.4$ mm ... 8 mm were made to cover a broad range of relevant tissue parameters.



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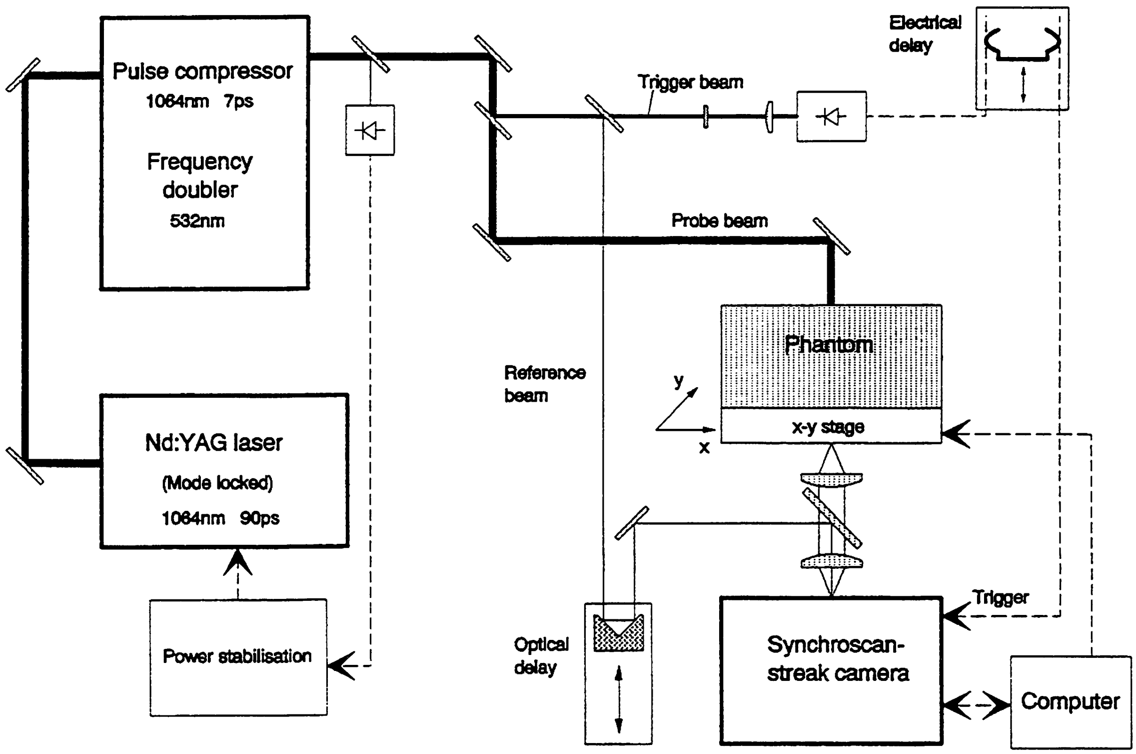


Fig. 1 Schematic set-up for time-resolved transillumination of turbid media.

## 2. EXPERIMENTAL METHOD

The experimental set-up for the time-resolved light transillumination[3] can be seen from Fig. 1. The laser system consists of a mode-locked Nd:YAG laser (82 MHz, 100 ps) with subsequent pulse compression (7 ps) and frequency doubling (532 nm).

A beam for triggering the synchroscan-streak camera (Hamamatsu C3681) and a reference beam are derived from the main beam. Unlike the probe beam, the reference beam does not traverse the phantom to be examined but is incident on the streak camera slit on the detection side. The probe beam traverses the phantom and finally reaches the detection side after many scattering events. The diffuse light from the detection side of the phantom is imaged onto the slit of the streak camera (50 µm × 6 mm) with a 1:1 magnification. The streak camera records the temporal profile of the incident light intensity and displays it as a spatial profile (time resolution 10 ps). The phantom is located on an x-y stage and can be moved in the horizontal plane under computer control. Milk was used as the turbid medium (whole milk powder). The scattering medium to be transilluminated had a thickness of 40 mm in all experiments and the optical parameters were set by diluting the milk and by adding ink.

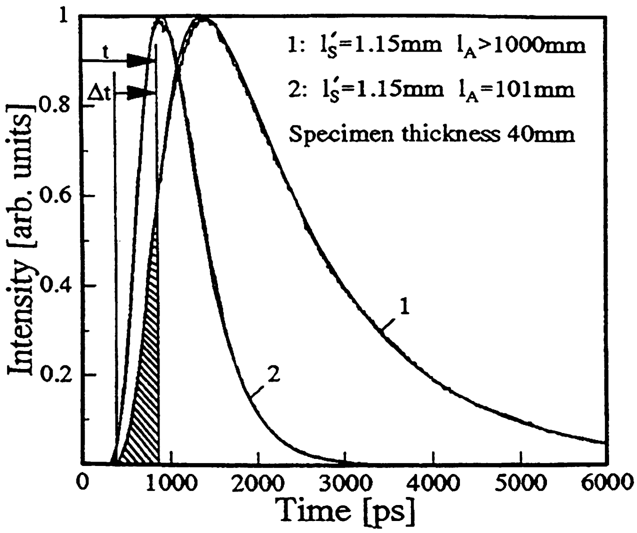


Fig. 2 Dispersion curves and associated theoretical curves.

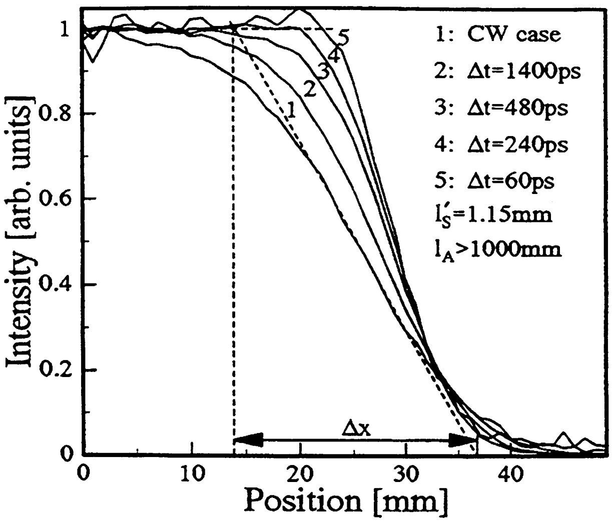


Fig. 3 Edge spread function for different integration times.

## 3. DETERMINING THE OPTICAL PROPERTIES WITH THE DIFFUSION MODEL

The diffusion model was used to determine the absorption coefficient $\mu_A$ and the reduced scattering coefficient $\mu_S' = \mu_S(1-g)$; $g$ is the anisotropy factor of scattering. A solution of the diffusion equation for a homogeneous medium can be derived.[4] It turned out that the diffusion model permits a very good description of light propagation in turbid media as long as the reduced scattering length $l_S' = 1/\mu_S'$ is smaller than 2 mm. By fitting the calculated dispersion curve to the measured curve, both the reduced scattering coefficient $\mu_S'$ and the absorption coefficient $\mu_A$ can be determined which gives the reciprocal optical path lengths.[5] Fig. 2 shows two measured dispersion curves (normalized) and the corresponding theoretical curves for a scattering medium of 40 mm thickness and two different reduced scattering lenghts $l_S'$. The correspondence of the measured dispersion curves with the theoretical curves is very good.

## 4. TIME-RESOLVED MEASUREMENTS ON COMPLETELY ABSORBING OBJECTS

A quantitative statement is obtained about the spatial resolution attainable via time resolution from line scans via a sharp edge in the middle of a turbid medium.[6] The edge is always placed in the middle of the scattering medium, where the spatial resolution is worst. The optical parameters of the scattering medium selected for these experiments are $l_S' = 1.15$ mm and $l_A > 1000$ mm. Fig. 2 shows a temporal dispersed pulse associated with these optical parameters and defines a time-of-flight $t$ and a time gate $\Delta t$. The

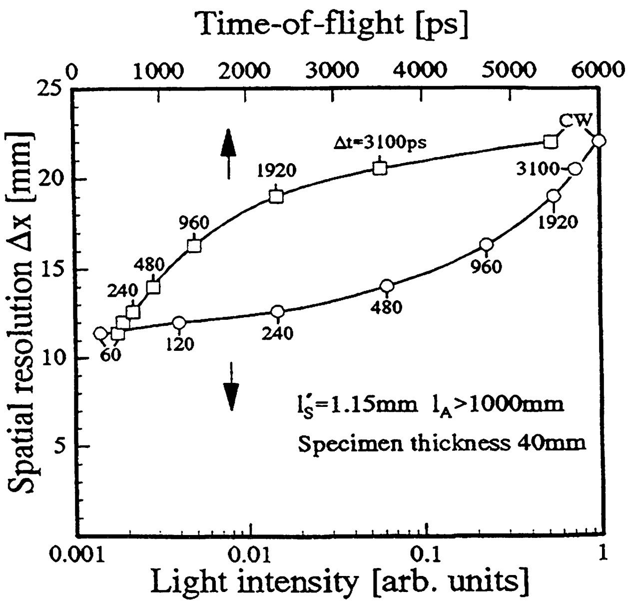


Fig. 4 Spatial resolution in relation to integration time and light intensity.

time-of-flight $t$ is given with respect to the incidence of the probe beam into the scattering medium, whereas $\Delta t$ represents the temporal width of the signal, of which the image information is derived. In the following the normalized intensity profiles result from integration over the respective time gates. Edge spread functions represent the intensity profile across a sharp edge for a fixed $\Delta t$.

Fig. 3 shows the edge spread function for five different time gates, the edge being located at a position $x = 30$ mm. Finally, the width of the resulting edge spread function is determined according to Fig. 3 and defined as the resolution $\Delta x$. Fig. 4 shows the spatial resolution $\Delta x$ for various integration times $\Delta t$. The smallest time gate that has been used was $\Delta t = 60$ ps. Reducing the time gate further only increases the noise but does not significantly improve the spatial resolution. The continuous wave case (CW case) is obtained by integrating the entire dispersion curve within the first 5 ns. The question as to how much intensity is lost by applying a time-of-flight restriction is of great practical interest. From Fig. 4 therefore, the spatial resolution can also be obtained in terms of the light intensity. The light intensity has been normalized to the CW case and is shown on a logarithmic scale. It becomes clear that with shorter integration times, any gain of spatial resolution must be paid for by a much faster reduction of signal light intensity. Under the conditions given in Fig. 4, the maximum gain factor attainable via time resolution ($l_S' = 1.15$ mm, $l_A > 1000$ mm) is 1.8 for a time gate of 120 ps. A further reduction of $\Delta t$ hardly increases the spatial resolution, while it impairs only the signal-to-noise ratio.

Measurements were also performed on bead pairs to determine the physical resolution by the Rayleigh-criterion. Two blackened beads with a separation equal to their diameter are placed at the middle of the scattering medium. The bead diameter is 6 mm for the smallest pair of beads and 8 mm for the biggest. The measurements were performed on phantoms with $l_S' = 0.40$ mm (Fig. 5a) and $l_S' = 8.2$ mm (Fig. 5b). In the CW case the individual beads cannot be resolved at either the large or for the small reduced scattering length. However for the smaller reduced scattering length, the individual pairs can be seen with higher contrast than in the case of larger reduced scattering length. The time gate for the measurement with $l_S' = 0.40$ mm has a value of $\Delta t = 240$ ps. A still smaller integration time hardly improves the spatial

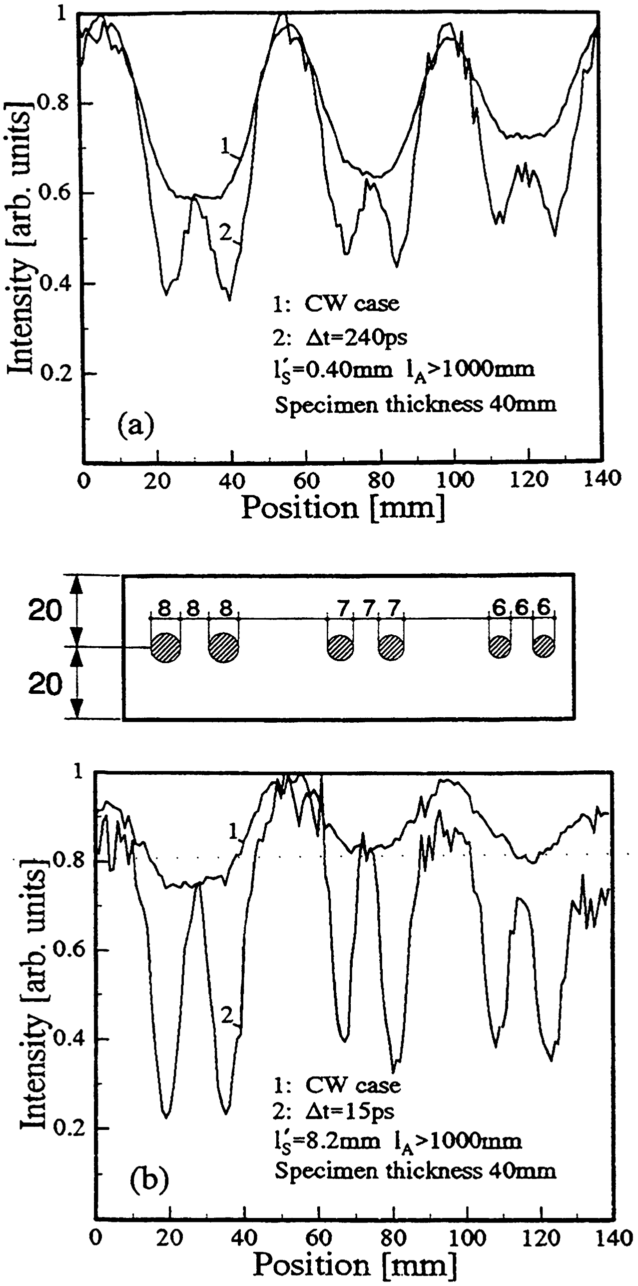


Fig. 5 Line scan over pairs of blackened beads with diameters of 6 mm to 8 mm. Reduced scattering lengths of the surrounding medium: 0.40 mm (a) and 8.2 mm (b).

resolution, but impairs only the signal-to-noise ratio. For $l_s' = 8.2$ mm, in contrast, with a time gate of $\Delta t = 15$ ps, the performance limit of the time resolving system is gradually reached. With time resolution, even the 6 mm beads can be distinguished in both cases, and more clearly for larger reduced scattering lengths than for smaller ones. Quantitative measurements on an edge phantom underscore the statement that the benefit of the time resolution increases with increasing reduced scattering lengths up to $l_s' = 8$ mm.[7]

## 5. TIME-RESOLVED MEASUREMENTS ON PARTIALLY TRANSPARENT OBJECTS

The detection of completely absorbing objects in the surrounding scattering medium represents a special case. Measurements were also carried out to demonstrate the sensitivity of the time-resolving technique with respect to partially transparent objects that differ from their environment in terms of scattering and absorption. Fig. 6 shows a line scan over two rods from plexiglass with diameters of 6 mm and 8 mm in a turbid medium with $l_s' = 1.15$ mm and $l_A > 1000$ mm. With a short integration time of $\Delta t = 30$ ps, even the 6 mm rod can be detected with a very good contrast. In the CW case, however, the rods can not be detected at all in contrast to the blackened bead pairs (Fig. 5). Here, the time resolution is particularly efficient, as the time-of-flight of the photons that traverse the plexiglass rods is shorter. Fig. 7 shows a line scan over a bead pair with bead diameters of 10 mm. The absorption length in the beads is $l_A = 15$ mm, with negligible scattering. As the beads are neither completely absorbing nor completely transparent, a signal increase is apparent with decreasing integration time ($\Delta t < 480$ ps) for the time-resolved case in contrast

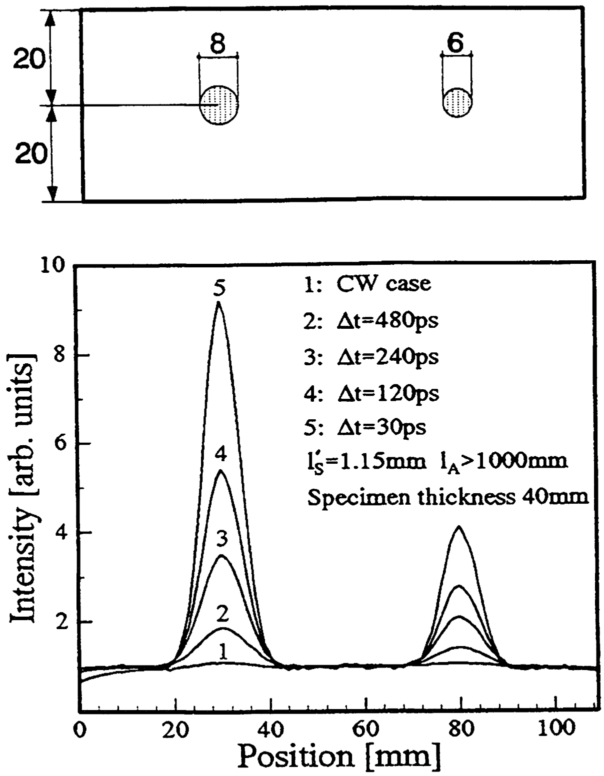


Fig. 6 Two rods from plexiglass with diameters of 6 mm and 8 mm.

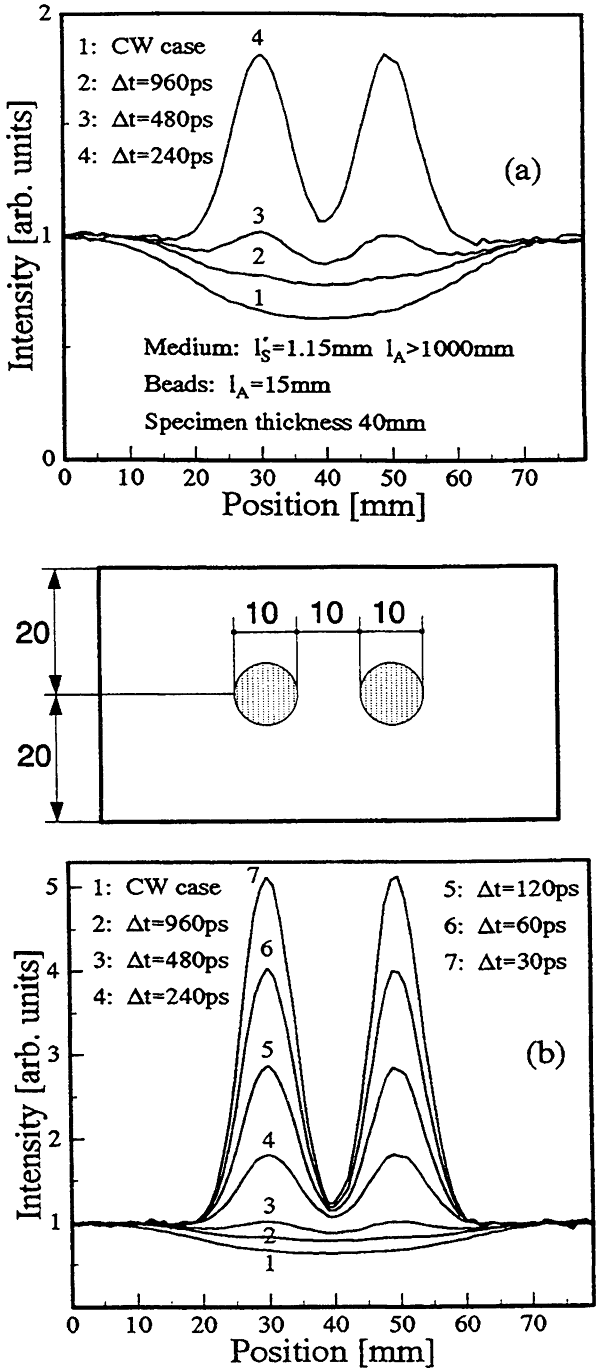


Fig. 7 Bead pairs from tinted plastic with a absorption length value of 15 mm. Minimum integration time: $\Delta t = 240$ ps (a) and $\Delta t = 30$ ps (b).

to the CW case ($\Delta t > 480$ ps), for which a signal reduction can be observed (Fig. 7a). The beads in the scattering medium become apparently more transparent with decreasing integration time and the increasing spatial resolution allows the pair of beads to be resolved. With decreasing integration time $\Delta t = 240$ ps ... 30 ps (Fig. 7b), the contrast is clearly improved.

This behavior is understandable as photons from the surrounding scattering medium traverse the plastic bead several times due to the low scattering there. Owing to the absorption occurring in the bead, and depending on the number of the traverses, either an increase or a reduction in the signal is obtained. The number of traverses depends on the respective time gate. The smaller the time gate, the less frequently are the beads traversed by the corresponding photons.

## 6. SUMMARY

The phantom experiments described here show clearly that the use of time-resolving techniques in the transillumination of turbid media offers a more or less clear gain in spatial resolution. For completely absorbing objects, this gain depends critically on the optical parameters of the surrounding medium, as the measurements of the blackened beads in Section 4 show. With partially transparent objects, in contrast, the measurement results in general are complex but allow us to conclude that the time resolution is especially advantageous in such cases. However, because only a few percent of the transmitted light can be used due to the time-of-flight gating, practical applications are generally restricted. They may be prohibited due to excessive measuring times.

## 7. ACKNOWLEDGEMENT

We would like to thank A. Oppelt and his coworkers, especially K. Klingenbeck-Regn and O. Schütz for their support and helpful cooperation. Our thanks also go to H. Bartelt and colleagues. Special gratitude is due to M. Guntersdorfer and E. Wolfgang for their general encouragement.

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