Fiber dispersion in time domain measurements compromising the accuracy of determination of optical properties of strongly scattering media

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Abstract. Limitations in the accuracy of measurements of optical properties (absorption and scattering coefficients) of strongly scattering media that are due to temporal dispersion inside the detection fibers of a time-of-flight setup were investigated for a tissue-like phantom. It is shown that the absorption and reduced scattering coefficients may be overestimated by up to 90% (depending on length and numerical aperture of the fibers) if the instrumental response measurements for the setup are performed by direct illumination of the tip of the detection fibers with collimated short laser pulses. However, the accuracy can be improved significantly if a thin layer of scattering media is used in front of the detection fibers during the response measurements. The relevance of the investigated dispersion effects is discussed with respect to frequency-domain measurements as well. © *2003 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.1578088]

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1 Introduction

The determination of optical properties, in particular the absorption coefficient μ_a (measured at different wavelengths) and the reduced scattering coefficient μ_s', of strongly scattering tissue is one of the main tasks in biomedical optics.[1–5] Various methods for measuring these optical properties of tissues have been reported. Integrating spheres were used for *in vitro* investigation of diffusely reflected and transmitted light with isolated tissue samples.[6] Noninvasive determination of *in vivo* optical properties was achieved by analysis of diffusely reflected or transmitted continuous wave (c.w.) light using several source–detector separations.[7] Improved *in vivo* measurements of optical properties of tissues were reported using intensity-modulated light.[8] The most advanced method for noninvasive *in vivo* determination of optical properties is based on time-resolved measurement of picosecond light pulses transmitted through or diffusely reflected from the tissue.[9,10] The temporal spreading of the light pulses contains information about the optical coefficients to be determined.

In practice, time-resolved measurements are often performed by time-correlated single-photon counting (TCSPC), measuring distributions of times of flight of photons (DTOF) through the tissue. Optical coefficients are determined by fitting a theoretical DTOF to experimental data. It is well known, however, that generally the instrumental response of the measuring system cannot be neglected; i.e., the experimental DTOF does not represent the true impulse response of the tissue. Thus deconvolution of the measured DTOF with the overall instrumental response is required to obtain the true optical parameters. Alternatively, the theoretical curve can be convolved with the instrumental response before fitting the data. In either case, it is crucial for the accuracy of the analysis that the instrumental response function must be known as accurately as possible.[11]

It is the purpose of this paper to analyze the influence of temporal dispersion effects in the detection fibers or fiber bundles—as usually employed—on the instrumental response, and to investigate the consequences of these effects on the accuracy of the optical properties evaluated. In particular, a method for the proper determination of the response function as suggested recently by Schmidt et al.[12] is investigated in more detail. Furthermore, we will discuss how fiber dispersion may affect the results of frequency-domain experiments as well. It is worth noting that the temporal dispersion effects discussed in the following pages are some of the most dominant contributions to the overall instrumental response, in particular if longer ($\geqslant 2$ m) fibers with a high numerical aperture (e.g., NA = 0.54) are used, as is often the case.

2 Experimental

The optical setup is illustrated in Fig. 1. A diode laser (PDL 800 system from PicoQuant GmbH, Germany) emitted pulses of 100-ps duration at a repetition frequency of 64 MHz and at a wavelength of 687 nm. The mean power of the laser light was 0.75 mW and a beam 1 mm in diameter was directly illuminating the phantom.

The light transmitted through the phantom was collected opposite the source point and routed into the detection optics by a fiber bundle. Four commercially available fiber bundles with different properties were investigated. The bundles were constructed from multimode glass fibers with a typical diameter of 70 μm. Their lengths and numerical apertures are sum-

Fig. 1 Experimental setup.

Fig. 2 Instrumental response measurements using various effective numerical apertures obtained by changing the diaphragm diameter. The measurements were performed with the Schott bundle (NA $=0.54$, $l=3.6$ m), illumination with short (≈ 100 ps) input laser pulses, and a thin paper in front of the entrance face.
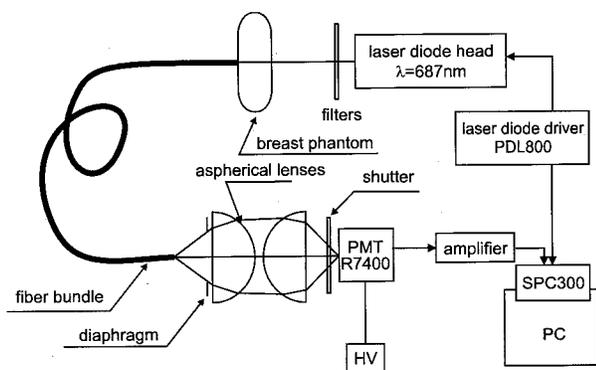
marized in Table 1. The overall transmission of light by the bundles varied between 50 and 60%.

To study the influence of the numerical aperture on the accuracy of the optical properties determined in more detail, the effective numerical aperture of the detecting setup was varied with the help of a diaphragm located in front of the detection optics. A metal package photomultiplier tube (PMT) (R7400U-02, Hamamatsu Photonics GmbH, Germany) was used as a photon counting detector. The exit face of the fiber bundle was imaged onto the multiplier photocathode surface by two aspherical lenses ($f_1 = 37$ mm, $d_1 = 52$ mm; $f_2 = 38.5$ mm, $d_2 = 50$ mm). The output pulses of the photodetector were amplified and distributions of the times of flight of photons were measured by time-correlated single-photon counting (SPC 300, Becker & Hickl GmbH, Germany). Distributions of times of flight were accumulated in 1024 channels, each 20.8 ps in width. The data acquisition times were typically 10 s for phantom measurements and 1 s for response measurements, respectively. Neutral-density filters were inserted to obtain count rates on the level of 800 kHz for a fully opened diaphragm.

The phantom consisted of a polymer host containing monodispersed quartz glass spheres with a diameter of 0.5 μm as scatterers and an IR absorbing dye as absorber. The shape of the phantom was close to that of a slightly compressed female breast, i.e., a slab of 4 cm thickness with rounded edges, as used for optical mammography.[13] The measurements were performed on a spot where lateral distances to the edges of the phantom were not less than 3 cm. The refractive index of the phantom was 1.55.

Table 1 Properties of fiber bundles investigated.

Bundle #	Manufacturer	Diameter mm	Length m	NA
1	Schoelly	5	1.5	0.22
2	Loptek	4	1.5	0.54
3	Loptek	4	3	0.54
4	Schott	5	3.6	0.54
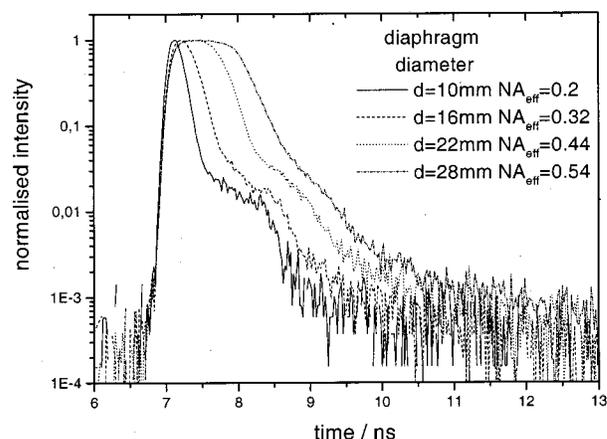
Several methods to determine the response function of the setup were employed. First, the so-called direct response was measured by directly illuminating the tip of the detecting bundle with the laser beam in a setup similar to that proposed by Ntziachristos et al.[14] Second, the response was measured after placing thin diffusers in front of the detection fiber bundle. Two kinds of diffusers were employed for this purpose: a sheet of white paper (100 μm thickness, 80 g/m^2) and a milky white opal coating (450 μm thick) flashed onto one surface of a glass plate (Edmund Optics).

The optical properties of the phantom were evaluated by fitting the photon flux density obtained from the solution of the diffusion equation[15,16] for an infinite slab to the measured distributions of the times of flight of photons. The extrapolated boundary conditions were applied.[17] The instrumental response was taken into account by performing convolution of the theoretical curve with the response in each step of the fitting procedure. In practice, only that part of the measured DTOF between the 5% levels of the maximum value was fitted. Time zero was fixed according to response measurements. The DTOFs were corrected for the differential nonlinearity of the TCSPC electronics.

3 Results

The inherent instrumental response function as limited solely by the laser pulse duration, the photodetector, and the TCSPC electronics was determined as 170 ps FWHM. The influence of the effective numerical aperture of the detector setup, including the fiber bundle on the response, is shown in Fig. 2. It is important to note that a thin, strongly scattering medium (white paper) was placed in front of the detection fiber bundle to ensure excitation and propagation of all higher transverse modes within the NA of the fibers. The paper was thin enough so that pulse broadening by scattering in the paper itself could be neglected. In measurements reported by other authors,[18] the mean time of flight was about 5 ps at a wavelength of 700 nm using a similar sheet of paper (with a basis weight of 90

g/m^2). The use of a thin diffuser leads to much stronger dispersion effects than the direct illumination of the entrance face of the fiber or fiber bundle, as will be discussed later. As can be seen from Fig. 2, the response is almost unaffected if a low effective NA is used, whereas a broadening of the response up to an FWHM of 1 ns was observed with an increase of the effective NA.

The observed time spread inside the fibers is well known to result from different effective propagation speeds of photons for various transverse modes within the (effective) NA. It can be derived from the group delay[19] as

$$\Delta t = \frac{nl}{c_0}\left(\frac{1}{\sqrt{1-\dfrac{NA^2}{n^2}}}-1\right), \quad (1)$$

where n is the refractive index of the core material, l the length of the fiber bundle, and c_0 the speed of light in vacuum. Assuming a glass fiber (bundle) with $l=3.6$ m, NA $=0.54$, and $n=1.5$, the highest-order mode is delayed by 1.3 ns in comparison with the lowest-order mode. Assuming the same number of photons in all modes within NA, this leads to a rectangular pulse of the width $2\sigma=0.75$ ns (where σ^2 is the variance of the pulse), which is in good agreement with experimental observations. The temporal dispersion caused by imperfect imaging with the aspherical lens setup was estimated to be less than 30 ps, and the dispersion caused by different lengths of individual fibers in the fiber bundle (assuming $<0.1\%$) is less than 20 ps for $l=3.6$ m; i.e., both can be neglected in comparison with mode dispersion.

The reduction of intensity with decreasing diameter of the diaphragm (i.e., decreasing effective NA) is shown in Fig. 3. For these measurements the Schott fiber bundle ($l=3.6$ m) with a high NA (0.54) was used. If a scattering medium (phantom, paper, or opal glass) is placed in front of the bundle, the whole NA is filled by light and the diaphragm starts to cut off intensity at a diameter of about $d=26$ mm, which corresponds to an effective NA of 0.54 (which is identical with the NA of the bundle as provided by the manufacturer). Without a scattering medium (i.e., direct illumination), mainly low-order modes propagate and the cutoff in intensity appears at a diaphragm diameter of $d=14$ mm, which corresponds to an effectively illuminated NA of about 0.32.

The results concerning the influence of the effective numerical aperture on the width 2σ of the measured pulses without a scattering medium (direct response) and using a sheet of paper, opal glass, or a thick phantom as scatterers, respectively, are summarized in Fig. 3 as well. Whereas for the direct response the pulse width is almost unaffected, the measurements with paper and opal glass resemble an increase in width from opening the NA. Apart from the thick, scattering breast phantom, the influence of the instrumental response on the width of the DTOF is clearly visible.

This influence has consequences for the calculation of optical properties, as can be seen in Fig. 4. If the correct instrumental response—measured with the help of a thin diffuser—is used for convolution of the theoretical curve to fit the experimental data, the calculated absorption as well as the
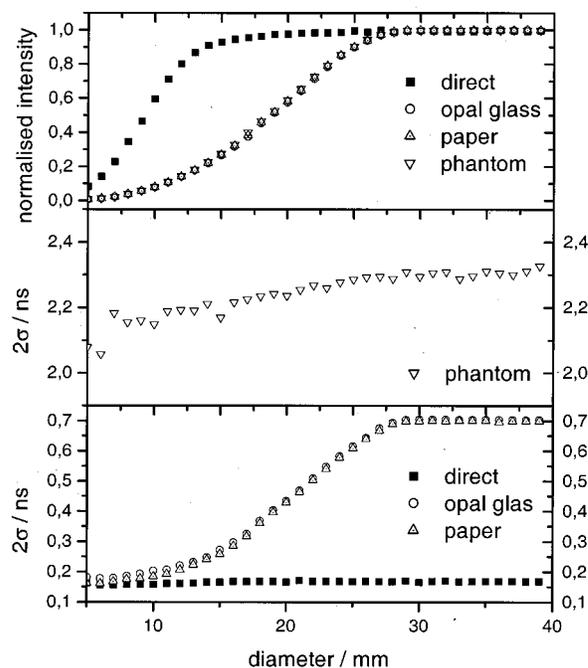

Fig. 3 Normalized intensity and width of the pulses (expressed as double the standard deviation 2σ) versus the diameter of the diaphragm measured using various scatterers in front of the entrance face of the Schott bundle (NA$=0.54$, $l=3.6$ m). Note that for small diameters of the diaphragm ($d<7$ mm), the width of the response is not affected by temporal dispersion of the fiber bundle, i.e., is given by the inherent response (laser pulse duration and detector).

reduced scattering coefficients almost do not depend on the fiber bundle employed or on the effective NA, etc. If, however, the narrow instrumental response from the direct measurement is used instead, the optical properties are strongly overestimated. These problems obviously do not occur with short bundles of low NA.

In principle, the discussed dispersion effects can be reduced by using graded-index instead of step-index fibers. However, the cladding in such fibers is relatively thick and the optical filling factor of bundles built from graded-index fibers is inferior to that of step-index fiber bundles, causing considerable reduction in the light collection efficiency.

The observed dispersion effects are not only present in time-resolved measurements but are also important for frequency-domain techniques because the phase shift of the modulated light intensity depends on temporal dispersion within the detection bundle as well. This was verified by performing a zero-phase measurement using a frequency-domain spectrometer (ISS Inc., Champaign, Illinois) at a modulation frequency of 110 MHz, with and without a thin diffuser in front of the detection bundle. The phase shift was measured and the mean time of flight was evaluated for a 3-m-long detection bundle with an NA$=0.46$ at four wavelengths: 750, 780, 810, and 830 nm. The differences between mean times of flight for diffuse and direct zero-phase measurements ranged between 610 and 700 ps. Consequently, proper zero-phase measurements with the help of thin diffusers are rather impor-
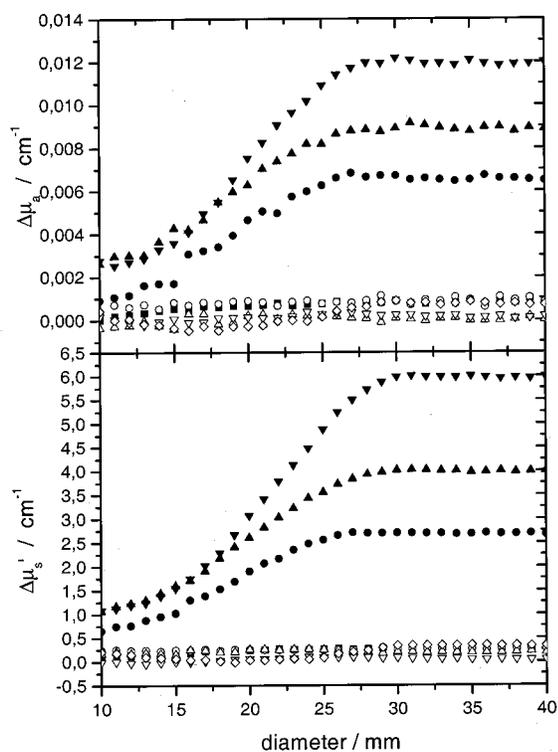
Fig. 4 Deviation of optical properties from their correct values (μ_a = 0.014 cm^{-1}, μ_s' = 8.5 cm^{-1}) versus the diameter of the diaphragm measured with different bundles for direct (closed symbols) and diffused (open symbols) responses. The following symbols refer to measurements obtained with the use of different fiber bundles ■, □—Scholly bundle, NA = 0.22, l = 1.5 m; ●, ○—Loptek, NA = 0.54, l = 1.5 m; ▲, △—Loptek, NA = 0.54, l = 3 m; ▼, ▽—Schott, NA = 0.54, l = 3.6 m.

tant for absolute measurements with frequency-domain devices as well.

4 Conclusions

Limitations in the accuracy of optical properties determined by time-resolved transmission measurements of short laser pulses through strongly scattering media have been investigated with respect to the numerical aperture and length of the optical detection fibers or fiber bundles employed. It was found that a remarkable broadening of the instrumental response as a result of modal dispersion [even for short l = 1.5-m bundles of high (0.54) NA] may influence considerably the optical properties determined. Consequently, the overall time resolution must be measured properly using a thin diffusing medium (e.g., white paper or opal glass) in front of the detecting bundle to fill the whole NA of the fiber in the same manner as during tissue measurements. The results obtained reveal that the use of such a thin diffuser allows all modes to be filled uniformly and provides an excellent way of measuring the response function properly. In contrast, (incorrect) response measurements without such a diffuser resulted in an overestimation of optical properties up to 70% (90%) for μ_s' (μ_a) for a 3.6-m-long fiber bundle with an NA = 0.54.

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