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Original Research Article

Estimation of light detection efficiency for different light guides used in time-resolved near-infrared spectroscopy

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ABSTRACT

Time-resolved near-infrared spectroscopy is a technique enabling the assessment of changes in oxygenation and perfusion of tissue with depth discrimination. A challenge in time-resolved measurements remains to provide sufficiently high efficiency of photons detection together with high temporal resolution of the setup. The aim of this study was to compare the performance of different fiber bundles and liquid light guides which can be used in time-resolved near-infrared spectroscopy measurements. The comparison was carried out by measurements of the instrument response function and of the responsivity of the optical detection system equipped with different types of light guides. The responsivity was estimated employing a test phantom with known diffuse transmittance factor. The results suggest that application of liquid light guides provides higher efficiency of photon collection in comparison to fiber bundles which are typically used in tissue optics instrumentation.

1. Introduction

Several optical techniques are widely tested as tools for monitoring and imaging of tissue optical and hemodynamic parameters. Near-infrared spectroscopy (NIRS) is one of the classical techniques developed and applied since more than 25 years [1–4]. The NIRS technique has significant advantages (mobility of the equipment allowing for bedside measurements, noninvasiveness) in respect to the other established imaging techniques (like computed tomography, magnetic resonance imaging or single photon emission computed tomography). The NIRS technique has several variants and the most common are continuous wave [5,6], frequency domain techniques [7,8] and time resolved measurements [9–12]. It was reported that the time-resolved variant of the NIRS technique can be used for depth discrimination of the measurement of absorption changes

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in brain studies [13–15] and for characterization of optical properties of tissues in breast tumor detection [16,17].

In measurements of light diffusely reflected or fluorescence light excited inside and reemitted from a turbid medium the efficiency of the detection system is of great importance. Particularly, in measurements on the adult human head large interoptode distances should be used in order to provide deep light penetration through the brain cortex. For such large interoptode separation the number of reemitted photons is very limited [18]. In optical mammography (depending on measurement geometry) large volumes of tissue may be located between source and detector which may also lead to a very low fraction of the injected photons transmitted to the detectors [19,20]. Typically in a time-resolved near infrared spectroscopy (TR-NIRS) system the light remitted from the tissue is transmitted to the detector using light guides (fibers, fiber bundles). Their properties may significantly influence the efficiency of the collection of photons on the detectors. It was reported that the selection of the optical fibers may influence the quality of the data obtained in near infrared spectroscopy [21,22], due to the limited number of detected photons. As part of the ''Basic Instrumental Performance Protocol'' developed in the European project nEUROPt, a test was designed to assess the responsivity of the detection system of instruments in diffuse optical imaging and spectroscopy, i.e. the overall efficiency to detect light emerging from tissue [23]. This test can be applied to compare the effect of various technical solutions for the components of the detection system that typically consists of an optical fiber or fiber bundle, relay optics and a detector. For time-domain systems, an important characteristic is the instrument response function (IRF) that depends on the laser pulse width, the temporal resolution of the detector and light dispersion in the fiber optics.

The aim of the present study was to analyze the influence of the selection of light guides on the efficiency of light detection. Since the temporal dispersion that occurs in the fiber depends on its length and numerical aperture [24], we will also analyze the instrument response function (IRF) of the setup obtained for different light guides applied.

2. Methods

The optical setup used for the measurement is presented in Fig. 1. The system consists of two main modules. The emission module contains a femtosecond MaiTai laser operating in the wavelength range between 720 nm and 910 nm. The light pulses are generated at 80 MHz repetition rate. According to the wavelengths used in our previous in vivo measurements [10,25] the two $\lambda_1 = 760$ nm and $\lambda_2 = 830$ nm wavelengths were chosen in the present study. Light pulses were delivered to the surface of the responsivity phantom (details see below) without the use of any additional fiber. The power was adjusted by a neutral density filter mounted in the optical path of the beam.

The detection channel of the system was equipped with a cooled photomultiplier module (PMC-100-20, Becker&Hickl, Germany), detector controller (DCC-100, Becker&Hickl, Germany), and a dedicated time-correlated single photon counting (TCSPC) card (SPC-134, Becker&Hickl, Germany). The card was mounted in an industrial PC with 2.4 GHz clock and for the acquisition of the distributions of time of flights of photons DTOFs dedicated software (Becker&Hickl, Germany) was used. A reference photodiode (PHD-400-N, Becker&Hickl, Germany) was used to provide the synchronization signal for the TCSPC electronics.

The responsivity of the detection system was measured using a dedicated phantom manufactured by Physikalisch-Technische Bundesanstalt (PTB) with known wavelength-dependent diffuse transmittance factor [23]. The phantom consisted of a 2 cm thick cylinder of turbid material (diameter 105 mm) enclosed in a box made from black PVC. The laser light beam was illuminating the phantom at its center through a window in the wall of the box. On the other side of the box a 25 mm diameter central window enabled the fixation of arbitrary detecting bundles directly on the surface of the turbid medium.

The light transmitted diffusely through the phantom was collected using different light guides characterized in Table 1.

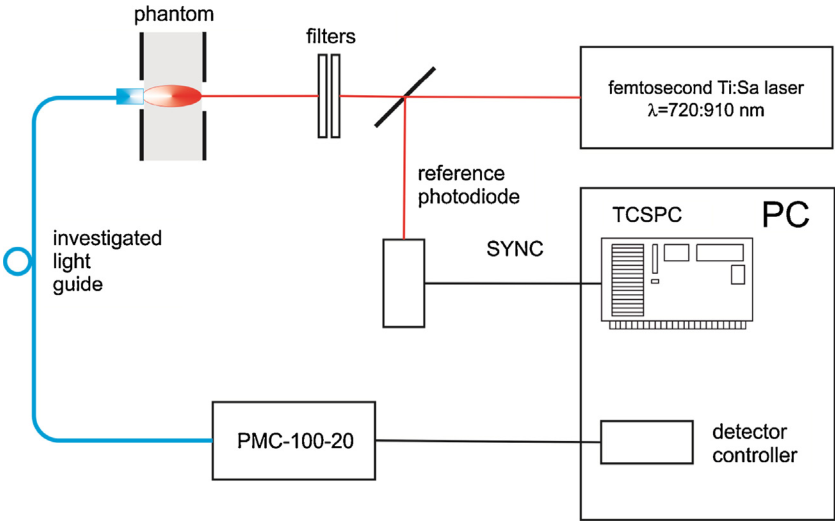

Fig. 1 – Schematic of the experimental setup.