TITLE PAGE

Citation Format:

Pirovano I., Re R., Contini D., Spinelli L., Torricelli A., "Instrument response function acquisition in reflectance geometry for time-resolved diffuse optical measurements," Diffuse Optical Spectroscopy and Imaging VII, edited by Dehghani H.,Wabnitz H., Proc. of SPIE Vol. 11074, Article number110742R, 2019

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DOI abstract link:

https://doi.org/10.1117/12.2526931

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Event: European Conferences on Biomedical Optics, 2019, Munich, Germany

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Instrument response function acquisition in reflectance geometry for time-resolved diffuse optical measurements

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ABSTRACT

Time-resolved (TR) techniques are exploited in many biomedical applications in order to find absolute values of absorption (μ_a) and reduced scattering (μ_s') coefficients that characterize biological tissues chemical and microstructure properties. However, the concomitant acquisition of tissue distribution time-of-flight (DTOF) and instrument response function (IRF) is necessary to perform quantitative measurements. This can be a non-trivial time consuming operation which typically requires to detach the optical fibers from the measurement probe (usually put in a reflectance configuration for in-vivo applications) in order to face them one to each other ("reference" geometry). To overcome these difficulties, a new IRF measurement method that exploit the "reflectance" geometry is here proposed. A practical 3D printed implementation has been carried out for a specific device to test the feasibility of this approach and if the IRF acquired in the "reflectance" geometry is equivalent to the "reference" one. A particular problem addressed is the determination of the temporal shift T_0 that can occur between IRF and sample DTOF. Two different approaches, based respectively on the curves barycenters difference and on a calibration phantom, are proposed. Both methods are valid and indifferently applicable according to specific measurement requirements. This allows "reflectance" IRF acquisition to be eligible as standard methodology for TR measurements.

Keywords: time-resolved measurements, instrument response function, temporal shift, custom-printed 3D system

1. INTRODUCTION

Many applications in biomedical optics, such as functional near-infrared spectroscopy (fNIRS) or optical mammography, exploit the theory of light propagation into highly diffusive media to non-invasively determine biological tissues optical properties. Time-resolved (TR) techniques allow to retrieve absolute absorption (μ_a) and reduced scattering (μ_s') coefficients[1]. In these methods, pulsed light at different specific wavelengths is injected into the tissue and the distribution of time-of-flight (DTOF) of photons, which have been re-emitted, is collected at a certain distance ρ. Most of the in-vivo applications require measurements in a reflectance geometry (e.g. brain, muscles). μ_a and μ_s' coefficients can be obtained by fitting the experimental data with the theoretical model derived from the diffuse theory[2]. To take into account the instrument contribution to the experimental curves modifications, data has to be de-convolved with the instrument response function (IRF) or the theoretical model has to be convolved with the IRF[3]. In fact, this one includes information about the time resolution of the TR instrument, (due to the optical fibers, detectors, …) causing a temporal dispersion of the DTOF. This work focuses on the aspects of practical acquisition of the IRF during a session of time-resolved diffuse optics measurements, providing an easy, general purpose and feasible methodology that can be executed by healthcare personnel in a critical environment such as clinics.

2. MATERIALS AND METHODS

2.1 Instrumental response function measurements configurations

To perform an accurate analysis for each TR measurement session, an IRF acquisition should be performed. For this purpose, usually injection and detection optodes are put one in front of the other and the system response is collected. This configuration is represented in Figure 1(a) ("reference" geometry) and it is the arrangement commonly used. As reported in the scheme, between the two injection and detection optical fibers we can insert an attenuation film due to power constrain, an anti-slip layer or a thin highly scattering layer (e.g. Teflon) in order to allow light to follow different random

Diffuse Optical Spectroscopy and Imaging VII, edited by Hamid Dehghani, Heidrun Wabnitz, Proc. of SPIE-OSA Vol. 11074, 110742R · © 2019 SPIE-OSA · CCC code: 1605-7422/19/$21 · doi: 10.1117/12.2526931

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paths before it is collected, as it happens in the sampled tissue. Due to the different pathways that photons can cover with respect to the sample measurements, a temporal delay between the IRF and tissue DTOF curves can be introduced. Since a convolution operation between the two has to be carried out, it is necessary to correct this temporal shift T_0 to gain a correspondence between the peaks axis time. In the described "reference" geometry, this parameter can be easily calculated with a good approximation by directly measuring the effective distance between the optodes and using the speed of light in air. However, to perform the IRF measurements in this way, it is necessary to unmount the optical fibers from the hosting probe employed during the sample measurements in reflectance geometry. This operation is not always possible: the commercial probes, for example, can not be typically disassembled. Moreover, it is a quite time consuming procedure, especially when executing in-vivo investigation on patients in a clinical setup. For all these reasons, we propose a new IRF's acquisition method in "reflectance" geometry, shown in Figure 1(b)), where there is no need to unmount the optical fibers or change the probe with respect to the in-vivo setup. Therefore, it is easy to use in every conditions, both in laboratory and in clinics. As schematically represented in Figure 1(b,) injection and detection fibers (separated by an interfiber distance ρ) face a reflective surface so that detector can collect the reflected photons (red arrows). This solution is applicable for difference kind of probe shape and dimensions. The only drawback of this configuration is that it is still necessary to determine the temporal shift T_0 that occurs between IRF and sample DTOF and this can not be directly achieved with a simple distance measurement as before, but it needs a specific calibration. In fact, since the reflective surface is not ideal, the path followed by each detected photon can not be calculated with geometrical optics laws.

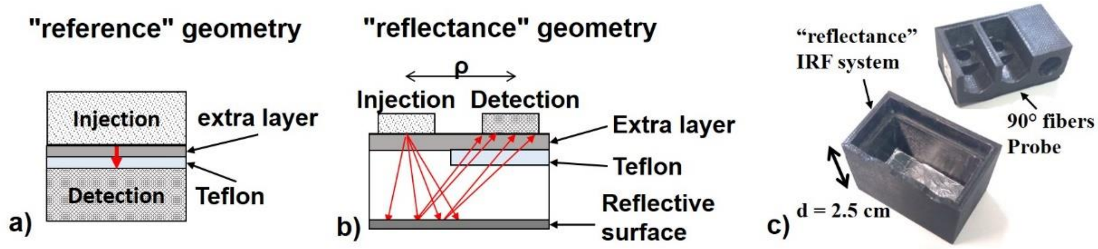

Figure 1. a) Scheme of IRF "Reference geometry" acquisition where injection and detection are facing each other. b) "Reflectance geometry" IRF model: optical fibers face a reflective surface. Mean path of photons travelling in air before being collected are highlighted (red arrows). c) 3D custom-printed probe and "reflectance" IRF acquisition system.

2.2 "Reflectance" IRF acquisition system implementation and characterization

A 3D custom-printed IRF acquisition system in "reflectance" geometry, shown in Figure 1(c), has been developed for an in-house built TR fNIRS device that is dedicated to muscle oxidative metabolism monitoring[4]. The probe used for measurements can host one injection and two detection 90° bended optical fibers at two different interfiber distances (ρ_1 = 1.5 cm; ρ_2 = 3 cm). Therefore, the IRF system has been tailored as a small box (53×36×33mm) with a reflective bottom side so that the probe can be easily hold into position. The distance between optical fibers and reflective surface (*d*) has been set to 25 mm. To define the optimal design, different factors have been tested at two wavelengths (690 nm and 830 nm) and interfiber distance of 3 cm, i.e. the influence of *d* on IRFs barycenter delay (t_{bar}) and preservation of shape and full width at half maximum (FWHM) in reflectance geometry. Results of this characterization are reported is section 3.

2.3 Temporal shift T_0 determination methods

As previously pointed out, it is necessary to take into account the temporal shift T_0 between the IRF and the measured DTOF that can not be simply measured in "reflectance" geometry configuration. We propose here two different approaches to retrieve T_0: the first one implies the acquisition of one IRF in the "reference" geometry with a known delay (Ref. T_0) with respect to experimental curves and the application of the following equation:

$$\Delta_{bar} T_0 = \Delta_{bar} - Ref.\ T_0 \tag{1}$$

where T_0 of the "reflectance" IRF ($\Delta_{bar} T_0$) is obtained as difference between the barycenters of the two system responses Δ_{bar}, corrected for the appropriate *Ref. T_0*. For the device employed, this is equal to 10.25 ps. The second method provides an estimation of the shift (*Est. T_0*) by fitting the DTOF measured on a calibration phantom with known absorption and reduced scattering coefficients (μ_a = 0.1 cm^{-1} and μ_s' = 10 cm^{-1} @ 660 nm).

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3. RESULTS

3.1 "Reflectance" IRF characterization

For the development of the "reflectance" IRF system it has been necessary to verify that the chosen distance between fibers and reflective surfaces does not introduce any non-linearity in the photons arrival time. For these reason, a series of measurements with *d* ranging from 5 mm to 35 mm has been performed. In Figure 2(a), a linear relationship between the barycenter position t_{bar} and *d* can be noticed; the two wavelengths are shifted of a constant amount. Considering this findings and overall dimensions of the system, a *d* of 25 mm have been chosen for the 3D printed implementation. Moreover, no shape distortion or relevant FWHM variation against the "reference" geometry acquisition have been observed, as shown in Figure 2(b).

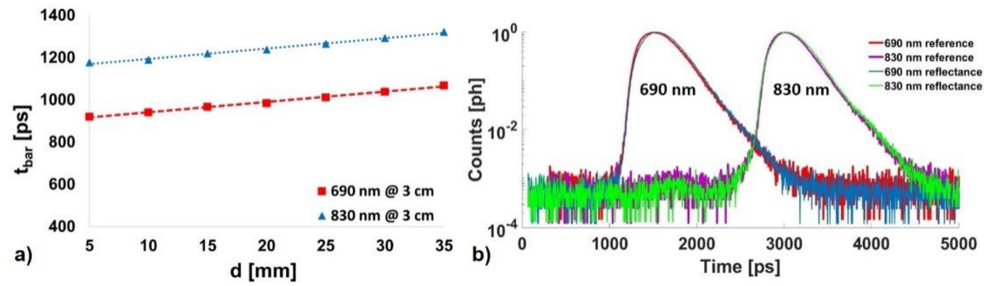

Figure 2. a) Relationship between IRF barycenters in "reflectance" geometry and distance between fibers and reflective surface at 690 nm and 830 nm. b) Comparison between "reference" IRFs, in red (690 nm) and purple (830 nm), and "reflectance" IRFs, blue (690 nm) and green (830 nm) curves.

3.2 Temporal shift T_0

Temporal shift T_0 characteristic of the described IRF measurement system has been calculated with both the proposed methods. Good performances and comparable values have been obtained for both approaches. With the first one we found a $\Delta_{bar} T_0$ equal to -236 (-234) ps at 690 (830) nm, while for the estimated T_0 values of -243 (-244) ps at 690 (830) nm have been retrieved. Hence, a difference less than 10 ps between the two methods have been found, which can be considered negligible given the 3.05 ps/channel resolution of the TR instruments used. This means that the two approaches can be indifferently used according to specific application.

4. CONCLUSIONS

Instrument response function is a crucial factor to perform quantitative measurements with time-resolved techniques. In this work, an IRF acquisition method in "reflectance" geometry is proposed, in order to guarantee accuracy and low-time consuming procedure under different circumstances, thus reducing the operator error dependency. In detail, a 3D printed solution has been developed for a specific device and feasibility of the approach has been validated. In particular, the problem of determination of the temporal shift T_0 that can occur between IRF and sample DTOF has been addressed and two comparable approaches have been proposed that can indistinctly be applied according to the available system. Future assessment measurements will be required to introduce the "reflectance" IRF configuration as standard method.

ACKNOWLEDGMENTS

This work was partially supported by Regione Lombardia and Fondazione Cariplo in the framework of the project EMPATIA@Lecco - EMpowerment del PAzienTe In cAsa - Rif. 2016-1428.

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