Performance evaluation of time-domain multispectral diffuse optical tomography in the reflection geometry

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Abstract: To evaluated capabilities of multispectral TD-DOT systems in reflection geometry, we performed a measurement campaign on multimaterial composition phantoms. Results show correct composition gradation of inclusions but still lack absolute accuracy.
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OCIS codes: (170.6920) Time-resolved imaging; (110.6960) Tomography; (100.3010) Image reconstruction techniques; (110.0113) Imaging through turbid media; (030.5260) Photon counting; (230.5160) Photodetectors.

1. Introduction

Optics in diffusive media is a modality which allows to characterize in-vivo and non-invasively the optical properties (absorption μ_a and scattering μ_s') of biological samples and may be used to diagnose pathologies like breast cancer, osteoarticular diseases or brain injuries like ischemia or hemorrhage. It also may be used to monitor brain activities during a variety of tasks or autologous tissues ("flap") in reconstruction surgery [1].

For most of the envisioned medical applications, the reflection geometry is preferable to eventually design a hand-held probe. For such a geometry, time-domain measurements, i.e. obtained with pulsed sources and time-resolved detectors are advisable since they contain specific information about the depth of light-matter interactions.

The technique can be coupled with tomography technique, i.e. using a set of source-detector pairs and performing reconstruction, so as to obtain 3D maps of optical properties at depths of a few cm, and coupled to multispectral approach, i.e. using multiple wavelengths, to decompose results on a material basis. In general, near infrared light is used for probing tissues since their absorption is minimum around 800 nm and the material basis considered is oxy/deoxyhemoglobin (HbO/Hb), which are physiologically of relevance and exhibit a specific spectral signature in this range of wavelengths.

To evaluate the capabilities of time-domain multispectral diffuse optical tomography to recover accurate material quantities, we conducted an extended experimental campaign on synthetic media (phantoms). Such media were built to mimick diverse Hb/HbO content scenarios. It consisted of one or two liquid inclusions with various material quantities dived at various depth inside a uniform liquid background. Due to the difficulties to find stable materials exhibiting spectral behaviors comparable to HbO/Hb, experiments were conducted with visible light (around 600 nm) where standard inks (black and cyan) can be used. Time-domain data processing was performed by using the Mellin-Laplace transform, either with the assumption of the inclusion positions, or without this assumption.

The paper is organized as follows: section 2 presents the time-domain multispectral acquisition system, the phantom making and the data processing procedure, section 3 presents an excerpt of obtained results and section 4 is a discussion.

2. Material and method

Acquisition scan:

We used the same setup as in [2] except that we changed the laser source by a supercontinuum laser (SuperK EXTREME, NKT photonics, 10 ps pulse width) and added a fast wavelength selection system, an acousto-optical tunable filter (AOTF, NKT Photonics). The backscattered light coming from the phantom was collected by two optical fibers at a distance of 30 mm

from the excitation fiber, each one connected to a SiPM detector [3] coupled to a TCSPC system. The whole scan over the phantom containing a single inclusion was done with 35 source positions (7 in x-direction and 5 in y-direction) and two detectors and 5 selected wavelengths (550, 580, 600, 630, 660 nm). A reference measurement was acquired far from the inclusion (at x = -4 cm from the center of the inclusion) where the medium is considered homogenous.

Multichromophore phantoms:

The phantom consist of a homogeneous liquid background and one or two inclusion(s) dived inside at depth ranging from 10 mm to 20 mm. The background is contained in a glass tank (a fish jar, volume 8.5 L) and is composed of a water-based solution made of Intralipid and cyan jet ink (μ_s'(600 nm) = 13.5 cm^{-1} and μ_a(600 nm) = 0.095 cm^{-1}). To prepare the multichromophore liquid inclusions, we use cyan and black inks (of HP ink-jet printer), which mimic Hb/HbO spectral behavior in the near infrared. So as to assess the quantitation performances and to draw gradual quantified plots of absorbing heterogeneities, we prepared gradual bi-chromophore inclusions (spectra in Fig.1). Liquid inclusions had a 1 mL volume and were contained in "balloons" created from cut parts of a laboratory disposable glove (made of natural latex and powder free, Ansell Ltd, color clear).

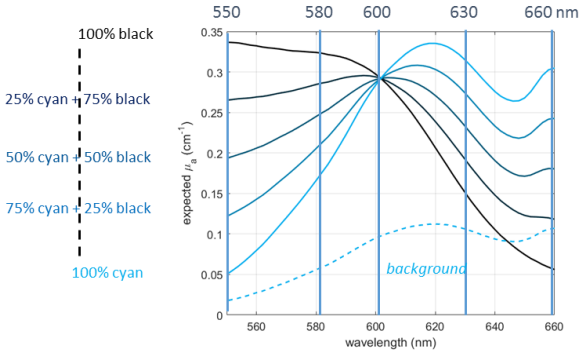

Fig.1 Spectra of the multichromophore "balloon" inclusions

Data processing:

The data processing method was the same as in [4], is limited for the study to absorption reconstruction (the diffusion been kept known and homogeneous), and is based on the Mellin-Laplace transform. The instrument response is eliminated by performing a cross convolution $Y^{(k)}(t)$ between reference measurements, $M^A(t)$, actual measurements $M^B(t)$ and their Greens function (known $G^{A)}(t)$ and estimated $G^{B(k)}(t)$ at iteration k) as described in Eq.1.

$$\begin{cases} M_{sd}^{A}(t) = IRF_{sd}(t) * G_{sd}^{A}(t) \\ M_{sd}^{B}(t) = IRF_{sd}(t) * G_{sd}^{B}(t) \end{cases} \Rightarrow \begin{cases} Y_{sd}^{(k)}(t) = M_{sd}^{B}(t) * G_{sd}^{A}(t) - M_{sd}^{A}(t) * G_{sd}^{B(k)}(t) \\ Y_{sd}^{(k)}(t) \approx -M_{sd}^{A}(t) * \int_{\Omega} d\vec{r}.G_{s}^{B}(\vec{r},t) * G_{d}^{B(k)}(\vec{r},t).\delta\mu_a(\vec{r}) \end{cases} \quad (1)$$

where $\delta\mu_a$ is the difference between the actual absorption at postion $\vec{r}$, $IRF_{sd}(t)$ is the instrument response function, and s and d are indexes on the source the detector and t is the time. Derivation from the diffusion equation leads to the equation at bottom right of Eq.1, which shows that the linear system to obtain absorption update $\delta\mu_a$ does not require the knowledge of the instrument response function. This equation is discretized in space (with the finite volume method) and time (with the Mellin-Laplace transform) so as to produce a linear system. $\delta\mu_a$ is obtained by solving this system with the conjugate gradient method and 10 iterations with absorption update and $G^{B(k)}$ recalculation are systematically done.

3. Some results

A typical excerpt from the set of analyses is shown on Fig.2. It corresponds to the case of one inclusion at a depth of 10 mm with material composition ranging from 100% cyan ink to 100% black ink reconstructed without spatial prior or with the a priori of the position of the inclusion. Quantified values obtained from such a set of reconstructions show correct localization

of the inclusion in all cases (up to a depth of 20 mm) and correct linear behavior between expected material decomposition and results. However, absolute quantification is not achieved yet since the linearity constants are less than 1. These constants are also decreasing with depth. Better results are obtained in the cases with spatial prior.

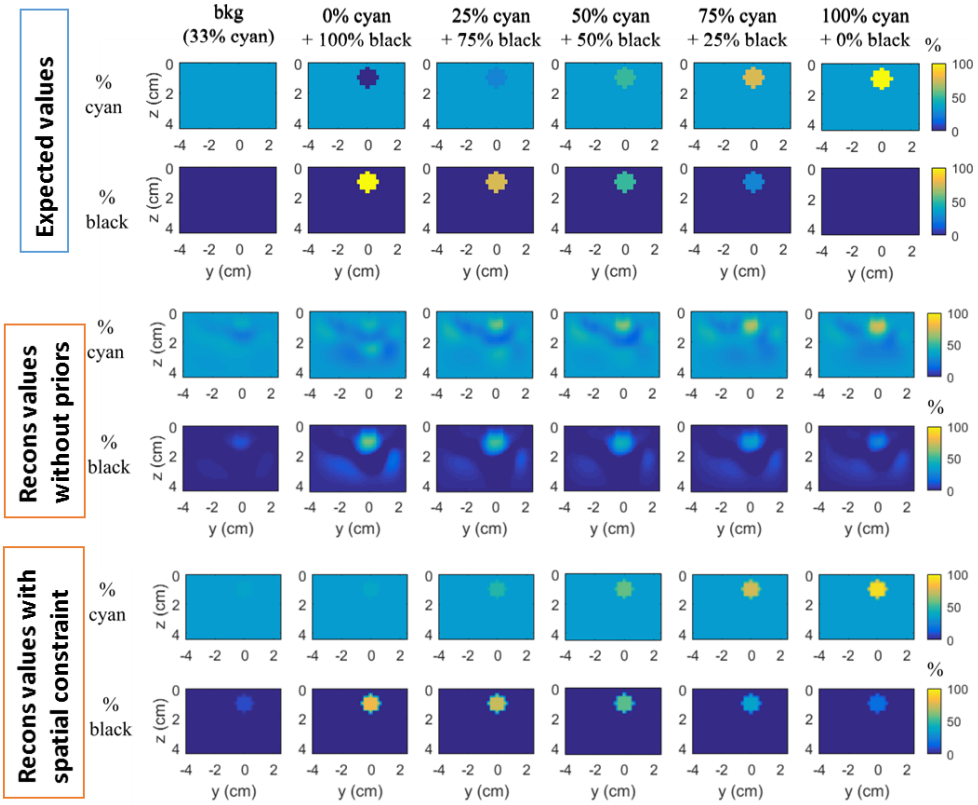

Fig 2 Material decomposition z-y slices of "balloon" inclusions at 10 mm depth. First row: expected values, second row: reconstruction without prior, and third row: reconstruction with spatial priors. Sources and detectors are located at the top.

4. Discussion and conclusion

We acquired a unique set of measurements with a time-domain multispectral system on a large range of bi-materials phantoms so as to evaluate the performance of a complete diffuse optical tomography system (apparatus + reconstruction algorithm). Results show very good localization of inclusions (up to 20 mm), good linear behaviors, but still suffer from lack of quantitation accuracy. Special attention must be paid on data processing. It is now performed by using Eq.1 (at bottom right), but such a procedure involving measurements convolution with Green's functions may lead to information loss. A better procedure is now regarded so as to achieve better quantifications. The whole set of reconstructions will be presented at the ECBO2017 conference.

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6. References

[1] L. Di Sieno, G. Bettega, M. Berger, C. Hamou, M. Aribert, A. Dalla Mora, A. Puszka, H. Grateau, D. Contini, L. Hervé, J.-L. Coll, J.-M. Dinten, A. Pifferi, and A. Planat-Chrétien, "Toward noninvasive assessment of flap viability with time-resolved diffuse optical tomography: a preclinical test on rats," J. Biomed. Opt. **21**, 25004 (2016).

[2] Di Sieno L, Zouaoui J, Hervé L, et al, "Time-domain diffuse optical tomography using silicon photomultipliers: feasibility study," J. Biomed. Opt. **21**(11) pp116002 (2016).

[3] 1. E. Martinenghi, L. Di Sieno, D. Contini, M. Sanzaro, A. Pifferi, and A. Dalla Mora, "Time-resolved single-photon detection module based on silicon photomultiplier: A novel building block for time-correlated measurement systems," Rev. Sci. Instrum. **87**, (2016).

[4] Judy Zouaoui, Laura Di Sieno, Lionel Hervé, et al, "Quantification in time-domain diffuse optical tomography using Mellin-Laplace transforms," Biomed. Opt. Express **7**(10), 4346-4363 (2016)