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Effects of ultrasound impedance matching fluids on diffuse optical measurements

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ABSTRACT

Diffuse optical imaging can be used to probe highly scattering media like biological tissue down to a depth of few centimeters, with spatial resolution limited by light scattering. Its combination with ultrasound imaging can potentially lead to medical imaging systems with, for instance, high specificity in the examination of tumors. However, the presence of the ultrasound coupling gel between probe and tissue can have detrimental effects on the accuracy of optical imaging techniques. Here we present an experimental study on the effect of ultrasound coupling fluids on diffuse optical spectroscopy (DOS) and diffuse correlation spectroscopy (DCS). We demonstrate on tissue-mimicking phantoms that the use of standard water-clear gels, providing a direct path for the light from the source to the detection point, can distort optical measurements generating strong underestimation of both the absorption and the reduced scattering coefficients in DOS measurements, as well as underestimation of the Brownian diffusion coefficient in DCS measurements. On the contrary, various turbid fluids demonstrate excellent performance in preventing this issue.

Keywords: Diffuse optical spectroscopy, diffuse correlation spectroscopy, ultrasound imaging, light scattering.

1. INTRODUCTION

There is an increasing interest of researchers in multimodal imaging diagnostic devices thanks to their potentiality to overcome limitations of each single measurement technique thanks to the combining of their strengths[1-3]. The combination of diffuse optical spectroscopy (DOS)[4], diffuse correlation spectroscopy (DCS)[5] and ultrasound (US) in particular can provide complementary compositional, functional and morphological information, thus increasing the diagnostic potential of non-invasive medical examinations. By assessing absorption (μ_a) and reduced scattering (μ_s') coefficients of tissues or of localized focal regions of tissues at some selected wavelengths, DOS can be used to estimate the tissue composition and microstructure[6]. On the other hand, by measuring the Brownian diffusion coefficient (D_B) of the tissue scattering particles (in large part red blood cells), DCS can estimate the microvascular blood flow. DOS and DCS can be used to probe tissues in depth, but their performances are in some cases plagued by their limited spatial resolution[7]. The combination with US offers the possibility to improve their accuracy in mapping optical and dynamic tissue properties. However, US measurements require the use of an US coupling fluid to match the acoustical impedance of tissues, avoiding the presence of air between the tissue and the US transducer. Unluckily, being usually water clear, that fluid provides easily a direct path for laser light between injection and collection points, thus potentially having detrimental effects on optical measurements[8].

In this paper we present the investigation of the effect of the US gel on DOS and DCS using different kinds of coupling fluids on tissue-mimicking phantoms. As proved, the use of a standard water-clear gel, providing a direct path for the light from the source to the detection point, can severely distort diffuse optical measurements, giving in particular a strong

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underestimation of both μ_a and μ_s' in DOS measurements, as well as a considerable underestimation of the D_B in DCS measurements. The addition of scattering particles to the coupling gel is able to completely delete these undesired phenomena, thus easy allowing precise combined optical-US measurements.

2. MATERIALS AND METHODS

Measurements were performed making use of an aluminum plate with 2 holes drilled to host injection and collection optical fibers (both with 1 mm core for DOS, a multimode 200 µm core for DCS source fiber, and a bundle 4x1 of single mode fibers for DCS detection) at 2 cm distance. Thanks to the strong optical reflection provided by the aluminum surface, the direct propagation of light between injection and detection points is maximized. On one hand, this will generate higher distortions with respect to what expected in real measurement conditions. On the other hand, fluids able to prevent direct light propagation with this probe will for sure perform even better with more realistic (i.e. less reflective) probes. The fiber tip is covered by a small glass window (0.55-mm thick gorilla glass, about 9 x 11 mm^2 size) glued to the aluminum plate inside a 0.55-mm recess, so that the probe presents a flat surface for the contact with the sample under investigation. This window prevents the accumulation of the fluid at the fiber tip that can introduce artifacts. We tested 5 different fluids between probe and phantoms: 1) a standard water-clear US gel (Cogel Ultrasound, Comedical s.r.l., Italy); 2) the same water-clear US gel with home-made 1% w/w dispersion of TiO_2 particles; 3) a standard turbid US gel (Polysonic® Ultrasound Lotion, Parker Laboratories Inc., USA); 4) a high viscosity body lotion (labeled hereinafter "Body lotion 1", Cutimed® Protect, BSN Medical GmbH, Germany); 5) a low viscosity body lotion (labeled hereinafter "Body lotion 2", Tena Skin Lotion, Tena s.p.a., Italy). For comparison purpose, we also tested a black velvet interface able to completely prevent direct light propagation, not usable for US investigations. DOS measurements were performed on 4 epoxy-resin homogeneous phantoms (nominal optical properties at 690 nm: μ_a = 0.05 cm^{-1}, μ_s' = 10 cm^{-1}; μ_a = 0.25 cm^{-1}, μ_s' = 10 cm^{-1}; μ_a = 0.05 cm^{-1}, μ_s' = 20 cm^{-1}; μ_a = 0.25 cm^{-1}, μ_s' = 20 cm^{-1}) using a state of the art time-resolved system[9] in the 600-1100 nm range in 50 nm steps, while DCS measurements were made on a liquid phantom[10] (nominal optical properties at 785 nm: μ_s' = 10 cm^{-1}, μ_a = 0.026 cm^{-1}) made of a solution of water and Lipofundin 20% (B. Braun Melsungen AG, Germany), enclosed by a thin Mylar sheet (already validated for diffuse optics), using a state of the art system[10].

3. RESULTS, DISCUSSION AND CONCLUSIONS

The first 2 columns of Figure 1 report the μ_a spectra of the 4 phantoms acquired with the 6 probe-phantom interfaces mentioned above, while the last 2 columns show the μ_s' spectra of the same phantoms. While all the fluids allow us to recover data comparable with those obtained using black velvet, the water-clear gel generates an evident underestimation of μ_a, which worsens either by increasing the phantom absorption or reduced scattering. The underestimation is even worst when looking at the μ_s' spectra, as the direct propagation of light is able to reverse the μ_s' trend with wavelength. Again, the underestimation worsens by increasing either the phantom absorption or its reduced scattering. The little μ_s' overestimation using the body lotion 1 can be due to a very high concentration of scattering particles, in agreement with its higher viscosity.

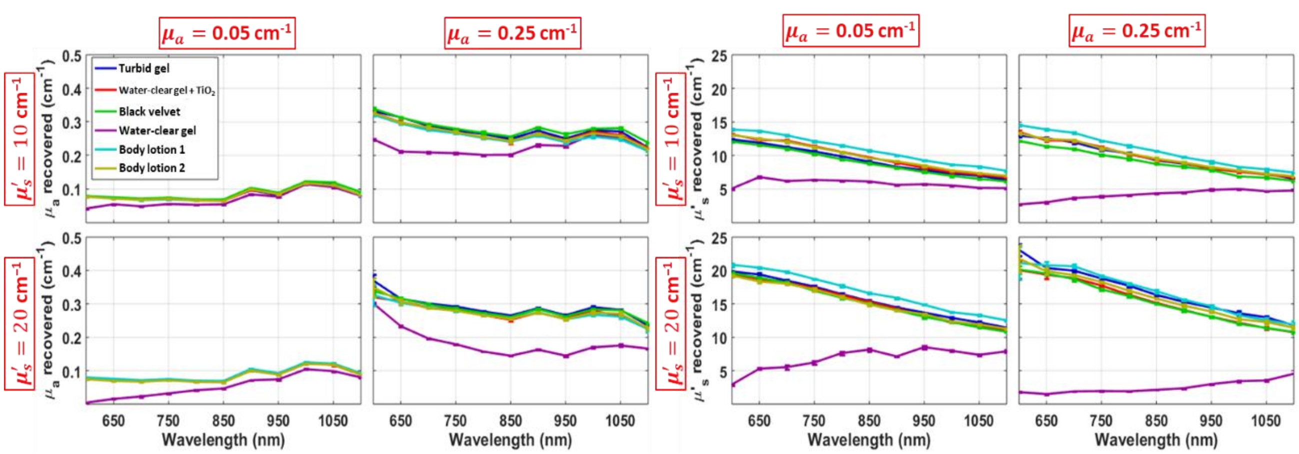

Figure 1. Absorption and reduced scattering spectra recovered for the 4 DOS phantoms with different interface materials.

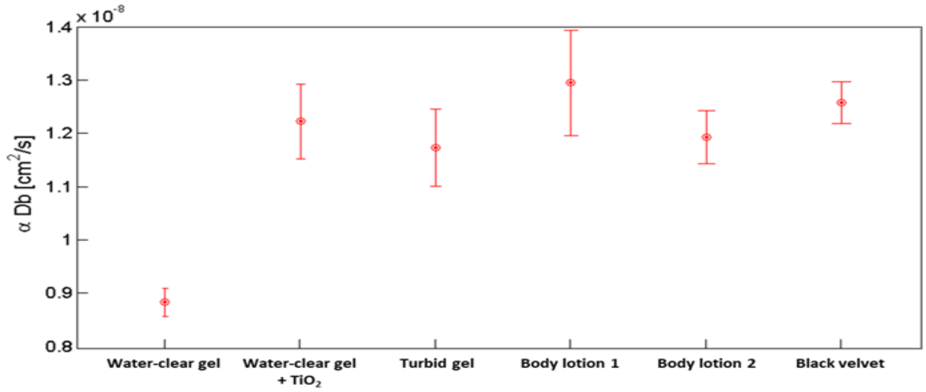

Figure 2. Brownian diffusion coefficients recovered for the DCS phantom with the 6 different probe interface materials.

In Figure 2 we report the Brownian diffusion coefficient D_B of the same liquid phantom measured by DCS considering all the 6 different configurations of the probe-phantom interface. Here, the same D_B measured using the black velvet is recovered (in the limit of the error bars) by using all the other fluids except the water-clear gel. In this case, the presence of the water-clear gel at the probe-phantom interface affects the measurements generating an underestimation of the measured D_B.

In conclusion, the use of a water-clear ultrasound impedance matching fluid can generate strong underestimation of optical and dynamic properties, in particular in conditions of high absorption or/and scattering of the sample under investigation. Turbid fluids (either home-made or commercially available) are able to efficiently prevent this undesired behavior, improving the accuracy in the quantification of optical and dynamic properties when diffuse optical imaging systems are coupled to US imaging systems. It is worth noting that such turbid fluids were able to suppress the direct light propagation between fibers even using a highly reflective probe surface as in this study, thus guaranteeing good performance with standard (i.e. less reflective) optical probes.

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