Phantom materials mimicking the optical properties in the near infrared range for non-invasive fetal pulse oximetry

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***Abstract*— An optical phantom of the maternal abdomen during pregnancy is an appropriate test environment to evaluate a non-invasive system for fetal pulse oximetry. To recreate the optical properties of maternal tissue, fetal tissue and blood suitable substitutes are required. For this purpose, phantom materials are used, which consist of transparent silicone or water as host material. Cosmetic powder and India ink are investigated as absorbing materials, whereas titanium dioxide particles are examined as scattering medium. Transmittance and reflectance measurements of the samples were performed in the spectral range from 600 nm to 900 nm using integrating sphere technique. The scattering and absorption coefficients and the anisotropy factor were determined using Kubelka-Munk theory. The results were used to compute the required mixture ratios of the respective components to replicate the optical properties of maternal tissue, fetal tissue and blood, and corresponding samples were produced. Their optical properties were investigated in the same manner as mentioned above. The results conform to the values of various types of tissues and blood given in the scientific literature.**

I. INTRODUCTION

Supply of oxygen during pregnancy is a crucial factor for the child's future physical and cognitive development. Especially during labor and delivery, a lack of oxygenation can lead to cerebral palsy as a result of intrapartum asphyxia [1]. Up to the present cardiotocography (CTG) and fetal bloodgas analysis are inherent parts of prenatal diagnostics. Due to some disadvantages of both approaches, optical measurement techniques have become an important field of research in prenatal diagnostics during the last decade. Near-infrared spectroscopy (NIRS) has been applied for determining the fetal oxygen saturation. Trans-vaginal pulse oximetry allows measurements of fetal oxygenation placing a sensor on the fetal head after rupture of the membranes. Further research focuses on transabdominal fetal pulse oximetry, which is also based on NIRS. This approach allows non-invasive and continuous determination of the fetal heart rate and oxygenation level. Different studies demonstrate the feasibility of this method [2]-[5], but it could not become established in clinical enviroment until the present.

An abdominal tissue phantom, including two independent artificial blood circulations, represents a suitable option for the validation of a pulse oximeter hardware system under laboratory conditions. Such a phantom has to meet different requirements with regard to optical properties and durability. Optical properties of maternal tissue, fetal tissue, and blood are to be determined and simulated.

As the durability of the phantom and the reproducibility of measurement conditions are indispensable prerequisites for the required application, a suitable host material as well as appropriate types of additives have to be found. Several optical tissue substitutes, which meet these requirements, have already been mentioned in the scientific literature. Thus, polyester and polyurethane resins [6], [7] as well as room temperature vulcanizing (RTV) silicone rubber [8], [9] and poly(vinyl alcohol) hydrogels [10], [11] are worth considering as phantom materials. Depending on the selected host material, different types of scattering and absorbing substances are added. For instance, scattering can be induced by titanium dioxide (TiO_2) [7], aluminium oxide (Al_2O_3) [8], [9] or microspheres [10], [14]. India ink [19], cosmetic powder [9] and molecular dyes [7] serve as absorbing media.

In this contribution suitable substitutes, which mimic the optical properties in the near infrared range of maternal tissue, fetal tissue and blood are investigated. The optical properties of the substitutes are measured using integrating sphere technique and are evaluated by Kubelka-Munk theory.

II. MATERIALS AND METHODS

A. *Tissue and blood mimicking materials*

To simulate the optical properties of maternal and fetal tissue, RTV silicon rubber (ELASTOSIL® RT 604 A/B, Wacker Chemie AG, Munich, Germany) is chosen as solid host material. This two component RTV silicone rubber is favorable as it is highly transparent and has a refractive index ($n = 1.404$) [8], [9], which is similar to the one of human soft tissue ($n = 1.33 - 1.8$) [12], [13]. Furthermore, its mechanical properties can be varied modifying the mixture ratio of the two component system [14]. Scattering is induced using TiO_2-particles (224227, Sigma-Aldrich Chemie GmbH, Taufkirchen, Germany), whereas cosmetic powder (Creme Puff Powder (deep beige), Max Factor, UK) is used as absorber. As cosmetic powder also contains scattering particles, its scattering influence has to be considered in the following calculations.

For sample preparation, the required amounts of cosmetic powder and TiO_2 respectively are dissolved in ethanol firstly. The resulting solution is then mixed with the main component of the RTV silicone rubber until a homogenous distribution of particles is achieved. At the same time the ethanol is evaporated by gentle heating. After the mixture has cooled down, the catalyst is added, which initiates the

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curing process. The material is then poured into a mold and entrapped air is removed using an ultrasonic bath. After five to ten days the samples obtain the final optical properties. The added amounts of absorbing and scattering medium vary from 0.3 to 2.0 % per weight and 0.5 to 1.5 % per weight respectively in order to identify the suitable quantities of additives.

In case of the required blood substitute, India ink is investigated as absorbing material. Therefore, various amounts of India ink (0.4 %, 0.6 % and 0.8 %) are mixed with distilled water to produce solutions of differing concentrations.

B. Sample analysis

The optical properties of the mentioned tissues and blood substitute are measured using the integrating sphere technique. In the following the measurement setups of total transmittance T_t, diffuse reflectance R_d and collimated transmittance T_c are described. Fig. 1 and Fig. 2a show the corresponding measurement setup for determining T_t. A high power supercontinuum laser (KOHERAS SuperK Power, NKT Photonics GmbH, Cologne, Germany) is used as light source. Two positive lenses expand and collimate the laser beam and the stop adjusts the light intensity. The samples are placed in front of an integrating sphere (K-100W, LOT-Oriel Group Europe, Darmstadt, Germany). For measurement a detector (ISP-75, Instrument Systems Optische Messtechnik GmbH, Munich, Germany) is used. The detector is connected via a fiber bundle to the scanning spectrometer (Spectro 320, Instrument Systems Optische Messtechnik GmbH, Munich, Germany). To measure the diffuse reflectance R_d the measurement setup depicted in Fig. 1 is used. The sample is placed behind the intergrating sphere and the corresponding port is opened (see Fig. 2b). Collimated transmittance T_c is measured using the detector. The sample is positioned between the collimator and the stop (∅ 2 mm) as depicted in Fig. 2c.

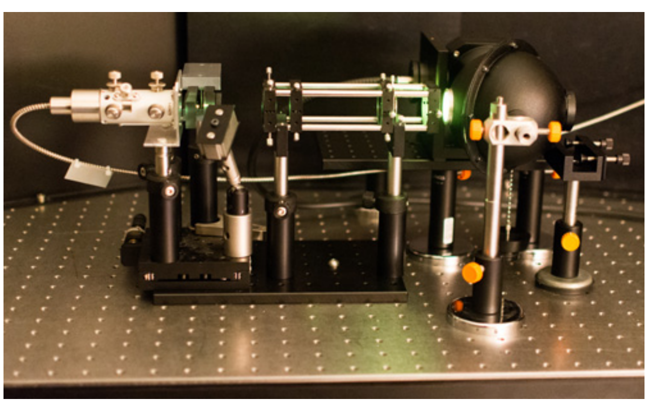

Fig. 1. Measurement setup of total transmittance and diffuse reflectance. Depending on the measurement scenario, samples are placed in front of or behind the integrating sphere.

C. Kubelka-Munk approach

Kubelka-Munk (KM) theory is a simplified approach to analyze light propagation inside a medium assuming that

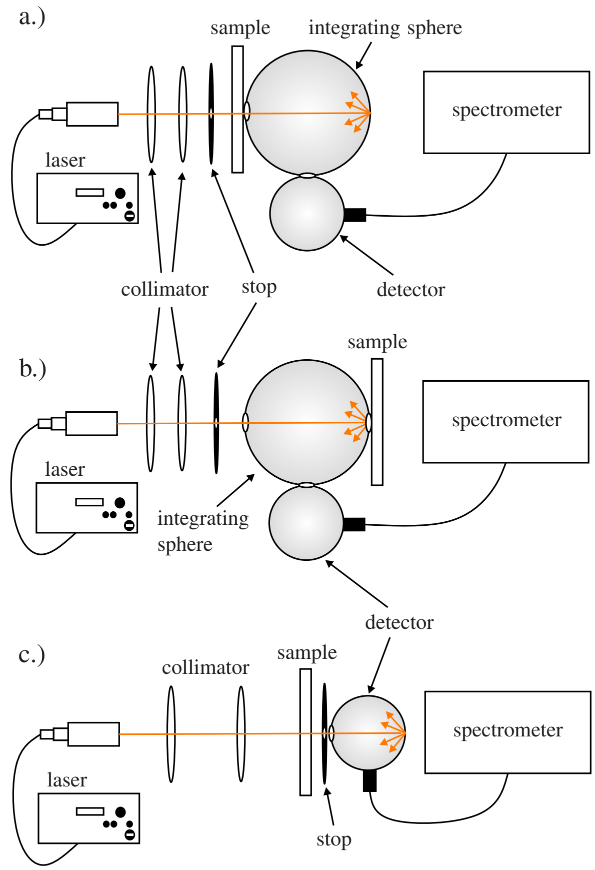

Fig. 2. Schematic diagram of integrating sphere measurements using a high power supercontinuum laser (KOHERAS SuperK Power, NKT Photonics GmbH, Cologne, Germany). a.) Measurement of total transmittance. The sample is placed in front of the integrating sphere (K-100W, LOT-Oriel Group Europe, Darmstadt, Germany); b.) Measurement of diffuse reflectance. The sample is positioned behind the intergrating sphere; c.) Measurement of collimated transmittance. The sample is placed between the collimator and the stop.

the sample is a one-dimensional slab without boundary reflections and the incident radiance is diffuse light [17]. As the requirement of scattering being significantly dominant over absorption is met, KM theory can be used for tissue analysis. The absorption and scattering coefficients (μ_a,μ_s) and the anisotropy factor g can directly be determined by measuring R_d, T_t as well as T_c [18]. The KM model can be described by

$$S = \frac{1}{bl} \cdot ln\left[\frac{1-R_d(a-b)}{T_t}\right] \qquad K = S(a-1)$$
$$a = \frac{1-T_t^2+R_d^2}{2R_d} \qquad b = \sqrt{a^2-1}$$
$$S = \frac{3}{4}\mu_s(1-g) - \frac{1}{4}\mu_a \qquad K = 2\mu_a$$
$$\mu_t = \mu_a + \mu_s \qquad \mu_s' = \mu_s(1-g) > \mu_a \tag{1}$$

where K is the KM absorption coefficient and S is the KM scattering coefficient. The transmittance μ_t is determined by

$$T_c = e^{-\mu_t l} \tag{2}$$

where l describes the sample thickness [18].

III. RESULTS

A. Optical properties of cosmetic powder, TiO_2 and India ink

Fig. 3 shows the absorption coefficients of cosmetic powder, TiO_2, India ink and homogenized milk normalized to a concentration of 1 % by weight. The corresponding scattering coefficients are depicted in Fig. 4. It has to be noted that the absorption induced by TiO_2 is significant smaller than the one of cosmetic powder and thus is neglected in the following considerations.

The anisotropy factor g of cosmetic powder, TiO_2 and India ink are shown in Fig. 5.

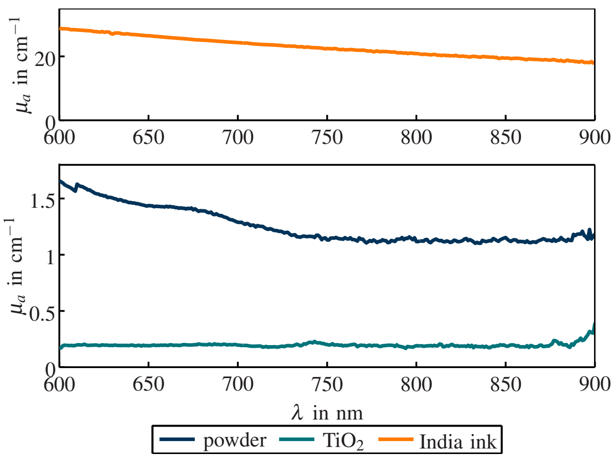

Fig. 3. Absorption coefficent of cosmetic powder, TiO_2 and India ink as a function of wavelength.

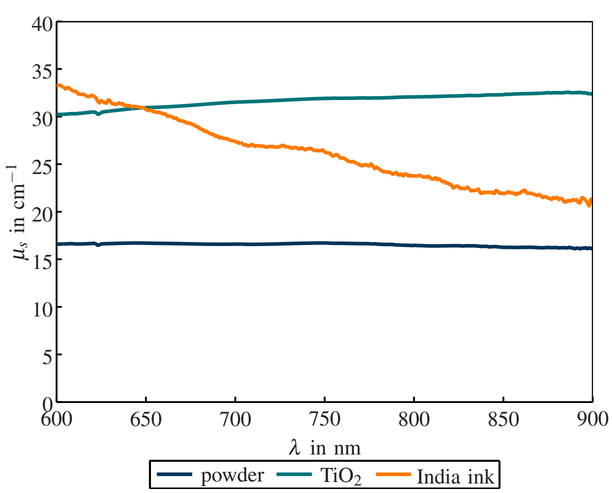

Fig. 4. Scattering coefficent of cosmetic powder, TiO_2 and India ink as a function of wavelength.

B. Replication of the optical properties of maternal and fetal tissue and blood

To produce phantom materials, which mimic the optical properties of the mentioned types of substitutes in a predictable manner, appropriate concentrations of additives have

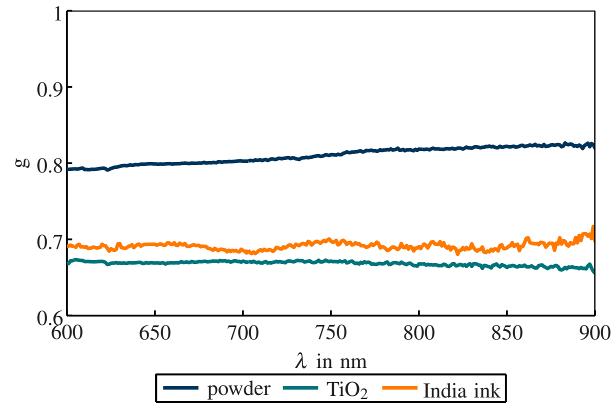

Fig. 5. Anisotropy factor of cosmetic powder, TiO_2 and India ink as a function of wavelength.

to be determined. In case of maternal tissue and fetal tissue suitable concentrations of cosmetic powder and TiO_2, which are added to the RTV silicone rubber, have to be found. Therefore, the following additive law can be used [9]:

$$\mu_t^{C+T} \equiv \mu_a^{C+T} + \mu_s^{C+T} = \mu_a^C + \mu_a^T + \mu_s^C + \mu_s^T \tag{3}$$

where $\mu_{t,a,s}^{C+T}$ represents total attenuation, absorption and scattering coefficients respectively of the host material mixed with cosmetic powder (^{C}) and TiO_2 (^{T}). Consequently follows:

$$\mu_a^{C+T} \cong \mu_a^C = \mu_a^{C\%} \cdot c^C \tag{4}$$

$$\mu_s^{C+T} = \mu_s^C + \mu_s^T = \mu_s^{C\%} \cdot c^C + \mu_s^{T\%} \cdot c^T \tag{5}$$

where $\mu_{a,s}^{C,T\%}$ represents the absorption or scattering coefficient of cosmetic powder and TiO_2 respectively normalized to a concentration of 1% by weight. The parameter $c^{C,T}$ stands for the concentration of the additive within the RTV silicone rubber. As already mentioned above, the absorption of TiO_2 is excluded in (4). Inserting the values given in the literature [15] for maternal and fetal tissue in μ_a^{C+T} and μ_s^{C+T}, suitable concentrations of both additives can be calculated.

The resulting values are shown in Table I.

TABLE I

CALCULATED CONCENTRATIONS (BY WEIGHT) OF COSMETIC POWDER, TiO_2 AND INDIA INK

mimicked tissue	**concentration c in %**		
	cosmetic powder	**TiO_2**	**India ink**
maternal tissue	0.0695	0.7473	-
fetal tissue	0.1085	0.7268	-
blood	-	-	0.1359

To find suitable amounts of India ink in the blood mimicking fluid, the absorption coefficient is determined by

$$\mu_a^I = \mu_a^{I\%} \cdot c^I \tag{6}$$

where $\mu_a^{1\%}$ represents the absorption coefficient of India ink normalized to a concentration of 1 % by weight. The determined concentration by weight c^I is computed by inserting values given in literature [15],[16] in μ_a^I and it is shown in Table I. Distilled water is used as host material. Samples of tissue and blood mimicking materials were produced using the calculated amounts of additives. Their optical properties are determined as described above and the results are compared with the corresponding data given in the literature [15],[16]. The respective values at a wavelength of 760 nm are listed in the following Table II.

TABLE II

OPTICAL PROPERTIES OF THE PRODUCED PHANTOM SAMPLES IN COMPARISON WITH SCIENTIFIC DATA AT 760 NM

mimicked material		**calculated value**	**existent data**
maternal tissue	μ_a	0.128 cm^{-1}	0.08 cm^{-1}
	μ_s	29.1 cm^{-1}	25 cm^{-1}
	g	0.63	0.8
fetal tissue	μ_a	0.165 cm^{-1}	0.125 cm^{-1}
	μ_s	30.35 cm^{-1}	25 cm^{-1}
	g	0.68	0.8
blood	μ_a	2.81 cm^{-1}	3 cm^{-1}
	μ_s	2.96 cm^{-1}	830 cm^{-1}
	g	0.721	0.99

IV. DISCUSSION

The optical absorption and scattering coefficients and the anisotropy factor of cosmetic powder, TiO_2 and India ink were determined. The computed absorption coefficient and anisotropy factor of cosmetic powder correspond with the results, which are given by literature [9]. TiO_2 can be used as an additional scattering medium, because of its relatively high scattering coefficient compared to the absorption coefficient. Based on these investigations, maternal and fetal tissue samples were produced. The results show slight differences compared to given values known from literature. This can be explained by the low absorption influence of TiO_2 which was neglected in the computed concentration amount as shown in equation (4). Measurements show that India ink has the largest absorption coefficient, which is also confirmed by literature [19]. For this reason the mixture is a suitable blood substitute in terms of absorption as shown in Table II. The scattering coefficient of India ink is not as high as the one of blood. This requires the addition of a further scattering material, whereas TiO_2 can not be used, because it is water-insoluble. For future work, an appropriate scattering medium (e.g. Intralipid) has to be found.

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