Drug quantification in turbid media by fluorescence imaging combined with light-absorption correction using white Monte Carlo simulations.

Xie, Haiyan; Liu, Haichun; Svenmarker, Pontus; Axelsson, Johan; Xu, Can; Gräfe, Susanna; Holm, Jesper; Cheng, Haynes Pak Hay; Svanberg, Sune; Bendsøe, Niels; Andersen, Peter; Svanberg, Katarina; Andersson-Engels, Stefan

Published in: Journal of Biomedical Optics

DOI: 10.1117/1.3585675

2011

Link to publication

Citation for published version (APA):

Total number of authors: 13

General rights
Unless other specific re-use rights are stated the following general rights apply:
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.
• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain.
• You may freely distribute the URL identifying the publication in the public portal.

Read more about Creative commons licenses: https://creativecommons.org/licenses/

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Drug quantification in turbid media by fluorescence imaging combined with light-absorption correction using white Monte Carlo simulations

Haiyan Xie
Haichun Liu
Pontus Svenmarker
Johan Axelsson
Can T. Xu
Susanna Gräfe
Jesper Holm Lundeman
Haynes Pak Hay Cheng
Sune Svanberg
Niels Bendsoe
Peter E. Andersen
Katarina Svanberg
Stefan Andersson-Engels
Drug quantification in turbid media by fluorescence imaging combined with light-absorption correction using white Monte Carlo simulations

Haiyan Xie, Haichun Liu, Pontus Svenmarker, Johan Axelsson, Can T. Xu, Susanna Gräfe, Jesper Holm Lundeman, Haynes Pak Hay Cheng, Sune Svanberg, Nils Bendsoe, Peter E. Andersen, Katarina Svanberg, and Stefan Andersson-Engel

Abstract. Accurate quantification of photosensitizers is in many cases a critical issue in photodynamic therapy. As a noninvasive and sensitive tool, fluorescence imaging has attracted particular interest for quantification in pre-clinical research. However, due to the absorption of excitation and emission light by turbid media, such as biological tissue, the detected fluorescence signal does not have a simple and unique dependence on the fluorophore concentration for different tissues, but depends in a complex way on other parameters as well. For this reason, little has been done on drug quantification in vivo by the fluorescence imaging technique. In this paper we present a novel approach to compensate for the excitation and emission light both for the absorption correction and the tissue fluorescence white Monte Carlo simulations combined with the Beer-Lambert law. This method shows that the correlated fluorescence intensity is almost proportional to the absolute fluorescence concentration.

Keywords: fluorescence; imaging; biomedical optics; tissues; optical properties; absorption; Monte Carlo; photon migration.

Paper 11047R received Feb. 2, 2011; revised manuscript received Apr. 6, 2011; accepted for publication Apr. 8, 2011; published online Jun. 1, 2011.

1 Introduction

Photodynamic therapy (PDT) has been clinically accepted to treat certain types of malignant tumors as well as some non-malignant diseases. In PDT a photosensitizer (PS) is administered either systemically or topically. It is activated by irradiating appropriate light to the sensitized tumor. As the PS absorbs light, the gained energy can be transferred to nearby oxygen molecules, leading to the formation of highly reactive oxygen radicals and thereafter tissue damage. PDT is a nonthermal photochemical reaction, which requires the presence of a photosensitizing agent (i.e., PS), oxygen and light, simultaneously.

In PDT, quantification of the PS in a noninvasive way is in many cases a critical issue, since light dosimetry, irradiation parameters, and therapeutic outcome depend significantly on the PS quantities distributed in the region of interest (ROI).

Various techniques have been proposed to quantify the PS concentration. In ex vivo animal experiments, high performance liquid chromatography (HPLC) of excised tissues is conventionally used as a gold standard for quantitative analysis of the PS concentration as well as for its pharmacokinetic behavior. Optical techniques can offer alternatives and be used in vivo. Among these techniques, absorption spectroscopy provides a noninvasive tool for PS concentration studies. However, it suffers from a relatively poor detection sensitivity, limiting its applicability. Most photosensitizing agents are, however, fluorescent, providing another possibility for measuring its concentration. Fluorescence has already been extensively used for tumor localization and to assess treatment progression during diagnostic screening or image-guided surgery to improve clinical decision-making and the therapeutic outcome (see e.g., Refs. 8–11).

Fluorescence spectroscopy (either in the point-monitoring or imaging mode) can also be used as a tool for PS concentration measurements. No tissue excision would be required in contrast to HPLC. Thus, it may constitute a tool for minimally invasive quantification studies providing in vivo capabilities. In these types of measurements, it is, however, a challenge to reduce the influence of the attenuation of the probing light. The signal depends not only on the concentration of the fluorophore but also on the optical properties, the detection geometry, and the tissue autofluorescence (i.e., the fluorescence from endogenous tissue fluorophores such as collagen or nicotinamide adenine dinucleotide (NADH)), etc. Ultimately, these dependencies tend to decrease the correlation coefficient between the fluorescence signal and the true PS concentration.

Address all correspondence to: Haiyan Xie, Lund University, Department of Physics, P.O. Box 118, SE-221 00, Lund, Sweden. Tel: 0046-46-222 3119; Fax: 0046-46-222 4250; E-mail: haiyan.xie@fysik.lth.se.
An alternative method would be to perform a tomographic reconstruction [fluorescence diffuse optical tomography (FDOT)]. Such a procedure would obtain the fluorescence signal per unit volume tissue compensated for the light attenuation. The reconstruction is achieved by fitting the collected boundary fluence for multiple source-detector pairs to a forward propagation model, for example, the diffusion model. This somewhat limits the geometries possible in the measurements. Furthermore, FDOT suffers from the requirement of a sophisticated system, greatly increasing the system expense. Moreover, an increased computation time, usually unknown background, and that the reconstruction algorithm most often is very ill-conditioned makes the technique difficult to use in practice.\textsuperscript{17-20} Image ratiometric quantification is therefore a commonly used method\textsuperscript{12} to correct for these properties. Svensson et al. have suggested and shown that an image ratio of the fluorescence signal from the PS over tissue autofluorescence signal could provide a capability in real-time PS quantification in a defined murine organ.\textsuperscript{31} However, different organs do not show the same dependence, probably due to their different optical properties. In Ref. 13, a double fluorescence/reflectance ratio was calculated for two different excitation sources. The excitation wavelengths were chosen to match the maximum and minimum of the fluorophore absorption spectrum. In this way, it was possible to compensate for the optical properties, and to obtain a signal that is only weakly dependent on these properties. This approach requires a sharp edge in the fluorophore absorption in order to facilitate a proper normalization. In Ref. 22, Themelis et al. employed a single fluorescence/reflectance ratio approach to correct for the light attenuation effects. They managed to improve the correlation between the fluorescence intensity and fluorophore concentration approximately from 2.5:1 to 1.6:1 for the epi-illumination imaging and from 1.8:1 to 1.2:1 for the transillumination imaging at a five-fold absorption variation for the phantoms they constructed. None of these techniques compensates adequately for the absorption at both excitation and emission wavelengths. The ratio-based methods are thus generally limited to certain special cases.

In this paper we present a novel model-based light-absorption correction approach to obtain the fluorescence intensity originating from the fluorophores to accurately quantify the PS concentrations from the 2D fluorescence images. This method utilizes time-resolved fluorescence white Monte Carlo (FWMC) simulations in combination with the Beer–Lambert law for light absorption. It takes into account details of the light propagation in homogeneous turbid media and thus does not require separate multispectral fluorescence measurements. The results on tissue-like phantoms containing Rhodamine 6G and organs of mice following systemic administration of a liposomal formulation of meso-tetra hydroxyphenyl chlorin (m-THPC), are presented and show an almost linear response of the corrected fluorescence intensities to the chemically extracted fluorophore concentrations measured from HPLC, regardless of the tissue optical properties. The sensitivity of the results to the optical properties variation of the media in the model are also presented.

2 Materials and Methods

The light-absorption correction method based on 2D fluorescence images was first validated with a set of well controlled tissue-like phantoms containing the fluorescent dye Rhodamine 6G. Then the PS concentration was evaluated in excised murine tissues and compared to the results from the gold standard in terms of HPLC analysis of extracted tissue samples.

2.1 Phantom Preparation

Twenty homogeneous liquid tissue phantoms were prepared by mixing water (192.3 ml), Intralipid (Fresenius Kabi, Uppsala, Sweden; 200 mg/ml, 7.3 ml), India ink (Pelican Fount, Hannover, Germany; 1:100 stock solution prepared in our lab, 0 ml, 0.5 ml, 1.0 ml, 1.5 ml, respectively), and Rhodamine 6G, a fluorescent dye with similar emission spectra to fluorescent proteins (Lambda Physik, Göttingen, Germany; a concentration of 10 μm solution, 0.2 ml, 0.5 ml, 1.0 ml, 1.5 ml, 2.0 ml, respectively). The ranges of ink and dye concentrations were chosen to match the absorption and fluorescence for small animals for both the excitation and emission wavelengths.\textsuperscript{23}

Each phantom was placed in a cylindric glass container. The thickness of the phantom was 3.1 cm. The absorption and reduced scattering coefficient were measured with a time-of-flight (TOF) spectroscopy system, described in detail elsewhere.\textsuperscript{24} The coefficients were measured at two wavelengths (632 and 660 nm). The absorption could be assumed constant over the wavelength range of interest, with the India ink as the absorber. For the reduced scattering, we assumed the relation

\[
\mu_r'(\lambda) = a \cdot \lambda^{-b},
\]

where the parameters \(a\) and \(b\) were determined from the measurements. The anisotropy factor was assumed to be 0.87 at these two wavelengths.\textsuperscript{25}

2.2 Photosensitizer

In the animal measurement, Fospeg\textsuperscript{®} (Biolitec AG, Jena, Germany), a liposomal formulation of the active ingredient m-THPC, or temoporfin, was employed as the PS.\textsuperscript{26, 27} Liposomes are designed as carrier and delivery systems with the aim of improving the tumor accumulation behavior of the PS during PDT. The PS was diluted in 50 μl of 5% glucose. All compounds were stored at 4 °C in the darkness. The extinction coefficients and fluorescence emission spectrum of m-THPC dissolved in ethanol were measured using a conventional spectrofluorometer (HORIBA Jobin Yvon GmbH, Unterhaching, Germany).

2.3 Animal Model

The study was performed on 30 female NMRI nu/nu mice (Harlan Winkelmann GmbH, Borchren, Germany). All animal experiments were carried out in compliance with the guidelines established by European Council Directive 86/909/EC and had been approved by the Thüringer Landesamt für Lebensmit- telsicherheit und Verbraucherschutz, Weimar. A suspension of HT29 human colorectal carcinoma cells (0.1 ml of 8×10\(^7\) cells/ml in 5% aqueous glucose solution) was inoculated subcutaneously 13 days before the measurements into the left and right hind thigh of six- to eight-week-old mice, weighing 22 to 25 g.

The optical properties for various murine tissues used in our data evaluation for some discrete wavelengths were obtained from Ref. 23. The reduced scattering coefficient was then extrapolated using Eq. (1). The absorption coefficient was
approximated in a similar way as a weighted sum of the concentrations of the blood (both oxy- and deoxy-hemoglobin) and water volume fractions in the organs, i.e.,

\[
\mu_a(\lambda) = C_{\text{diff}}(\lambda, R_{\text{vessel}}) \cdot S_B \cdot \left[ x \mu_{\text{HbO}_2}(\lambda) + (1-x) \mu_{\text{Hb}}(\lambda) \right] + S_W \cdot \mu_{\text{Hb}}(\lambda),
\]

(2)

where \( \mu_{\text{HbO}_2}(\lambda) \), \( \mu_{\text{Hb}}(\lambda) \), and \( \mu_{\text{Hb}}(\lambda) \) were the spectral absorption coefficients of oxy-haemoglobin (HbO\(_2\)), deoxy-haemoglobin (Hb) and water, respectively. \( x = \text{HbO}_2/ (\text{HbO}_2 + \text{Hb}) \). \( S_B \) and \( S_W \) were blood and water volume fractions, respectively in the different mouse organs. The factor, \( C_{\text{diff}}(\lambda, R_{\text{vessel}}) \), was introduced to extend the applicability of the diffusion theory in homogeneous media to shorter wavelengths than 650 nm, due to the fact that blood is not a homogeneously distributed absorber but a strong absorber concentrated in the discrete blood vessels.\(^{28}\) The mean vessel radius, \( R_{\text{vessel}} \), was set to 60 \( \mu m \).\(^{29}\) Numerical values for all parameters in the model were selected as in Ref. \(23\). Finally, the anisotropic factor was set to be 0.8 at both the excitation and emission wavelength.\(^{30}\)

2.4 Animal Procedures

Fospeg\(^{\circledR}\) was injected into the tail vein of the mice 13 days after the tumor cell inoculation, when the tumors had reached a surface diameter of approximately 5 to 8 mm, and protruded approximately 2 to 3 mm above the skin surface. After injection of Fospeg\(^{\circledR}\), the mice were kept in the dark and given food \textit{ad libidum} until the experiment was performed. The animals were then sacrificed at different times (0.5, 2, 4, 8, and 18 h) after the PS injection. Blood was removed rapidly by cardiac puncture and organs (muscle, liver, kidney, and lung) were excised for fluorescence imaging measurements followed by HPLC analysis. Five mice without PS injection were used as controls.

2.5 HPLC Analysis

Immediately following the fluorescence imaging, the tissue samples were snap frozen and stored in the darkness until analyzed using chemical extraction and HPLC analysis. In preparation for the HPLC analysis, tissue samples were homogenized by cutting into small pieces, freeze dried for 24 h using a freeze dryer (Alpha 1–4 LSC, Martin Christ Gefriertrocknungsanlagen GmbH, Osterode am Harz, Germany), mixed with methanol and dimethyl sulfoxide (3:5, volume:volume), and continuously shaken for at least 12 h in a vortex mixer (Merck Eurobit, MELB 1719, Lutterworth, UK) operating at 2400 rpm. All samples were then spun at 16,000 rpm in a centrifuge (Microfuge, Heraeus, Germany) during 5 min. 1.0 ml of each supernatant was transferred to an HPLC vial. Details of the sample preparations and HPLC analysis are described in Refs. \(21\) and \(31\). The results from the HPLC method of the excised tissue were used as gold standard for determining the drug concentrations. These values were correlated to the animal fluorescence measurements.

2.6 Fluorescence Imaging Measurements

Fluorescence images were acquired using the setup schematically depicted in Fig. 1. The excitation light was coupled into an optical fiber. The distal end of the fiber was positioned to obtain either a transillumination or an epi-fluorescence geometry.

The fluorescence images were acquired in a dimmed room to avoid any artifacts from background light. Background images without the excitation light were also acquired using the same filter wavelength.
lated by a reverse-emission accelerated Monte Carlo (MC)
dent on tissue type (or optical properties).

on fluorophore concentration could be reconstructed, indepen-
known. Thus, the linear dependence of the fluorescence intensity
law, if the temporal distribution of the escaping fluorescence is
ent absorption coefficients, leading to different absorbed frac-
the fluorophores. However, different media usually have differ-
escaping from the surface is proportional to the concentration of
coefficient and geometry but containing a different amount of
2.7 Light absorption correction
For a series of nonabsorbing media with the same scattering coefficient geometrically used for the simulation is a cylinder with a radius of $R$ and height of $Z$, as shown in Fig. 2. The optical properties of the medium at the excitation wavelength are described by the absorption coefficient $\mu^x_{\text{a}}$, the scattering coefficient $\mu^x_{\text{s}}$, and the anisotropy factor $g$. The corresponding parameters at the emission wavelength are $\mu^m_{\text{a}}$, $\mu^m_{\text{s}}$, and $g^m$, respectively. Furthermore, we define $t^x$ as the time an excitation photon takes from the excitation light source to exciting a fluorophore, and $t^m$ the time an emission photon takes from the fluorophore to the detector on the medium surface. For a nonabsorbing white medium with certain scattering coefficients $\mu^x_{\text{s}}$ and $\mu^m_{\text{s}}$, the fluorescence intensities detected at a radial position $r_D$ after time $t^x$ and $t^m$ are denoted as $F_W(r_D, t^x, t^m)$, the short term of $F_W(\mu^x_{\text{a}} = 0, \mu^x_{\text{s}} = 0, \mu^m_{\text{a}}, \mu^m_{\text{s}}, r_D, t^x, t^m)$. It could be simulated through a reverse-emission accelerated FWMC procedure, as defined in Ref. 33, by setting $\mu^x_{\text{a}}$ and $\mu^m_{\text{a}}$ to zero and convolving over space.

$F_W(r_D, t^x, t^m) = \int_0^Z dz \int_0^R dr \int_{-\pi}^{\pi} d\psi A_W(\mu^x_{\text{a}} = 0, \mu^x_{\text{s}}, r, z, t^x) \times \phi_{\text{em}}(r, \psi, z) E_W(\mu^m_{\text{a}} = 0, \mu^m_{\text{s}}, d, z, t^m), \quad (4)$

where $A_W(\mu^x_{\text{a}} = 0, \mu^x_{\text{s}}, r, z, t^x)$ is the probability per unit volume and unit time for an excitation photon to be absorbed at a fluorophore position $(r, \psi, z)$, after a time delay $t^x$ from the injection point; $E_W(\mu^m_{\text{a}} = 0, \mu^m_{\text{s}}, d, z, t^m)$ is the probability
per unit volume and unit time to detect a fluorescence photon which originates from the fluorescence emission point which is located at a radial distance $d$ and a depth $z$, after a delay $t_m$; $\phi_{\text{eff}}(r, \varphi, z)$ is the effective quantum yield, which is a constant in time and space and proportional to the fluorophore concentration. In our evaluation the decay of the fluorophore is assumed to be negligible. Values of input parameters used for the WMC simulations are stated in Table 1.

In the experiments, the excitation light was distributed over the medium surface. This effect was taken into account by

$$F_w(r_D, t^x, t^m) = F_w(r_D, t^x, t^m) \otimes S_{\text{Beam}}, \quad (5)$$

where $\otimes$ denotes the convolution, and $S_{\text{Beam}}$ is the beam intensity profile on the medium surface.

If absorption is added to this white medium at both excitation and emission, the corresponding fluorescence intensities, $F_A(r_D, t^x, t^m)$, can be derived analytically from $F_w(r_D, t^x, t^m)$ using the Beer–Lambert law:

$$F_A(r_D, t^x, t^m) = F_w(r_D, t^x, t^m) \exp \left[ -\mu_a^x t^x \right] \exp \left[ -\mu_a^m t^m \right], \quad (6)$$

where $v = c/n$ is the light speed in the medium with a refractive index $n$. Integrating over the time, we will get a signal corresponding to the recorded fluorescence signal from a pixel at a radius $r_D$, or a Cartesian position $(x, y)$ in the image, where $r_D = (x^2 + y^2)^{1/2}$. We denote this $F_{\text{image}}(x, y)$:

$$F_{\text{image}}(x, y) = F_{\text{image}}(r_D) = \int_{t^x} \int_{t^m} F_A(r_D, t^x, t^m) dt^x dt^m. \quad (7)$$

Then the total intensity from the image can be obtained by summing up all over the pixels:

$$F_{\text{image}} = \sum_{x, y} F_{\text{image}}(x, y). \quad (8)$$

By defining a calculated correction factor

$$\Delta \equiv \frac{\int_{t^x} \int_{t^m} F_A(r_D, t^x, t^m) dt^x dt^m ds}{F_{\text{image}}}, \quad (9)$$

where $\gamma$ denotes the surface integral, and ROI is the evaluated region of interest from which the fluorescence is measured, we get

$$F_{\text{image}} \cdot \Delta \propto \int_{t^x} \int_{t^m} \phi_{\text{ROI}} F_A(r_D, t^x, t^m) dt^x dt^m ds \propto \phi_{\text{eff}} \propto \text{Conc}, \quad (10)$$

where Conc is the fluorophore concentration to be determined. This indicates the corrected fluorescence intensity, $F_{\text{image}} \cdot \Delta$, will be proportional to the fluorophore concentration.

### 3 Results

#### 3.1 Time-Resolved Fluorescence Distribution from the FWMC Simulations

The simulated temporal distribution of the fluorescence signal $F(r_D, t^x, t^m, z_D)$ is plotted in Fig. 3. This corresponds to the detected signal at a surface of the simulated phantom at a radial distance $r_D = 5.0$ mm, where $z_D$ indicates if the detector is at the bottom (the left column, $z_D = 3.1$ cm, corresponding to the transillumination geometry) or the top surface (the right column).

![Fig. 3](image)

**Fig. 3** Simulated temporal distribution of the fluorescence for the phantom at $r_D = 5.0$ mm. The left column illustrates the fluorescence at $Z_D = 3.1$ cm, i.e., for the transillumination geometry. The fluorescence intensity has been normalized to its peak signal. The right column shows the corresponding data at $Z_D = 0$, i.e., for the epi-fluorescence geometry. The top row show the results for a white medium when all the incident photons were injected at the origin; in (b) and (e) a uniform flat beam was incident all over the surface of this white medium; while in (c) and (f) an absorption of $\mu_a^x = \mu_a^m = 0.37$ cm$^{-1}$ is added. In the simulations, reduced scattering coefficients of $\mu_s' = 10.07$ cm$^{-1}$ and $\mu_s'' = 8.30$ cm$^{-1}$ were used.

### Table 1 Input parameters for white Monte Carlo imaging

<table>
<thead>
<tr>
<th>No. photons</th>
<th>$\phi_{\text{eff}}$</th>
<th>$dz$ [µm]</th>
<th>$dr$ [µm]</th>
<th>$dt$ [ps]</th>
<th>$n_z$</th>
<th>$n_r$</th>
<th>$n_t$</th>
<th>$n_l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phantoms</td>
<td>$2 \times 10^6$</td>
<td>0.25</td>
<td>500</td>
<td>500</td>
<td>10</td>
<td>61</td>
<td>120</td>
<td>400</td>
</tr>
<tr>
<td>Murine tissues</td>
<td>$10^7$</td>
<td>0.25</td>
<td>40</td>
<td>40</td>
<td>1</td>
<td>125</td>
<td>200</td>
<td>150</td>
</tr>
</tbody>
</table>

### Table 2 Phantoms and Murine tissues

<table>
<thead>
<tr>
<th>Phantoms</th>
<th>106 0.25 500 500 10 61 120 400 400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murine tissues</td>
<td>107 0.25 40 40 1</td>
</tr>
</tbody>
</table>

### Table 3 Grid resolution and size

<table>
<thead>
<tr>
<th>Grid resolution</th>
<th>Grid size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_x$</td>
<td>$n_y$</td>
</tr>
<tr>
<td>61</td>
<td>120</td>
</tr>
<tr>
<td>125</td>
<td>200</td>
</tr>
</tbody>
</table>

---

*Journal of Biomedical Optics* 066002-5

June 2011  •  Vol. 16(6)
When a certain absorption was added to the white medium, the fluorescence signal in the point source was convolved with the beam intensity profile on the total surface. The result of that is shown in the middle row. The subplots in the top row show the results for a point source at the top center of a white medium, i.e., with zero-absorption. It can be seen that most of the excitation light has a large probability to be absorbed and the fluorescence reaches the detector within a much longer time in the transillumination geometry [Fig. 3(a)] than in the epi-fluorescence geometry [Fig. 3(d)]. For a flat light source with uniform power distribution irradiating all over the surface of the white medium, the fluorescence signal in the point source case was convolved with the beam intensity profile on the total surface. The result of that is shown in the middle row. The signal is increased by a factor of approximately one thousand. When a certain absorption was added to the white medium, Eq. (6) was applied to calculate the absorbed light. The results are illustrated in the bottom row. Photons with a long traveling time are absorbed, resulting in a decreased fluorescence signal.

For the phantom, the total simulation time is approximately 3 h for one single FWMC process, running on an Intel Duo Core 2-GHz processor. For the smaller grids corresponding to the animal case, the simulation time is approximately 10 h.

### 3.2 Phantom Measurements

Our light-absorption correction method was first tested on homogeneous well-controlled tissue-like phantoms. From the TOF measurement, the absorption coefficients of the phantoms with the same ink concentration were the same at both 532 and 600 nm, as the India ink absorption is very flat over this wavelength range. For different ink concentrations, the results were 0.37, 0.26, 0.14, and 0.012 cm$^{-1}$, respectively. The reduced scattering coefficients were measured and extrapolated to be 10.10 cm$^{-1}$ at 532 nm and 8.30 cm$^{-1}$ at 600 nm.

The simulated dependence of the correction factor on different absorption coefficients at the excitation and emission wavelength is shown in Fig. 4(a). For the four sets of phantoms with different absorptions, the correction factor was $\Delta = 5303$, 949, 87, and 2, respectively. The large variation in $\Delta$ illustrates that the fluorescence signal from the surface is heavily dependent on the optical properties of the absorbing medium. Figure 4(b) shows the correlation between the fluorescence signal and the fluorescent dye (Rhodamine 6G) concentrations before and after the light-absorption correction, respectively. The markers without circles represent the raw signals directly from the images, while the markers with circles representing the corrected fluorescent dye by multiplying the off-diagonal ratio $[F_{\text{image}}(652 \text{ nm})/F_{\text{image}}(525 \text{ nm})]$ and light-absorption correction method $[F_{\text{image}}(652 \text{ nm}) \cdot \Delta]$ were evaluated for the different types of murine organs. The results are shown in Figs. 7 and 8. The subplots on the left of Figs. 7 and 8 show the correlations between the raw fluorescence signals at 652 nm directly from the images and the PS concentrations. The slope of the linear fit varies from 5900 for muscle to 720 for lung (8.3:1). That is to say, no universal correlation curve could adequately fit

**Fig. 4** (a) Dependence of the correction factor on phantom absorption coefficients for the transillumination geometry. (b) Scatter plots showing the fluorescence signals captured at 600 nm before (markers without circles) and after (with circles) the light-absorption correction versus the true dye concentrations for liquid tissue-like phantoms, where the absorption coefficients are the same at the 532-nm excitation and 600-nm emission, i.e., $\mu_a = \mu_a^e = \mu_a^m$. The inset shows the same data in the semi-log scale.

$z_D = 0 \text{ cm}$, the epi-fluorescence geometry). The subplots in the top row show the results for a point source at the top center of a white medium, i.e., with zero-absorption. It can be seen that most of the excitation light has a large probability to be absorbed and the fluorescence reaches the detector within a much longer time in the transillumination geometry [Fig. 3(a)] than in the epi-fluorescence geometry [Fig. 3(d)]. For a flat light source with uniform power distribution irradiating all over the surface of the white medium, the fluorescence signal in the point source case was convolved with the beam intensity profile on the total surface. The result of that is shown in the middle row. The signal is increased by a factor of approximately one thousand. When a certain absorption was added to the white medium, Eq. (6) was applied to calculate the absorbed light. The results are illustrated in the bottom row. Photons with a long traveling time are absorbed, resulting in a decreased fluorescence signal.

For the phantom, the total simulation time is approximately 3 h for one single FWMC process, running on an Intel Duo Core 2-GHz processor. For the smaller grids corresponding to the animal case, the simulation time is approximately 10 h.

### 3.3 Animal Measurements

The extinction coefficients and fluorescence emission spectrum of m-THPC dissolved in ethanol are plotted in Fig. 5, which shows a high extinction coefficient at 405 nm and strong fluorescence emission at 652 nm.

For the animal measurements, the data from the HPLC method were regarded as the absolute PS concentrations. Figure 6 shows some fluorescence images of the murine organs ex vivo, acquired from the imaging setup. Both the image spectral ratio $[F_{\text{image}}(652 \text{ nm})/F_{\text{image}}(525 \text{ nm})]$ and light-absorption correction method $[F_{\text{image}}(652 \text{ nm}) \cdot \Delta]$ were evaluated for the different types of murine organs. The results are shown in Figs. 7 and 8. The subplots on the left of Figs. 7 and 8 show the correlations between the raw fluorescence signals at 652 nm directly from the images and the PS concentrations. The slope of the linear fit varies from 5900 for muscle to 720 for lung (8.3:1). That is to say, no universal correlation curve could adequately fit.
Fig. 6 Fluorescence images of some animal organs ex vivo captured at different emission wavelengths with an exposure time of 11 s. The color bars indicate fluorescence intensity after background subtraction. (a) The top row shows the images taken with the LCTF set to 652 nm (corresponding to the maximal drug fluorescence), while (b) the bottom row shows the images at 525 nm (tissue autofluorescence).

Fig. 7 Scatter plots showing (a) the fluorescence signals captured at 652 nm versus the HPLC values for individual organs, where a linear fit of the data points for each type of organs (solid line) is also shown; (b) the spectral ratio of the fluorescence intensities at 652 nm to that at 525 nm; and (c) the fluorescence signals after the light-absorption correction versus the HPLC values.

Fig. 8 Comparison of the linear fit slopes between the fluorescence signals and the HPLC values. The methods are the same as stated in Fig. 7.
the fluorescence imaging data and the HPLC values, mainly due to the varying optical properties of the tissue under investigation. As shown in the middle columns, the slope from the spectral ratio varies from 240 for muscle to 60 for liver (4:1:1). After the absorbed light is compensated for, using the optical properties of a different type of murine organs listed in Table 2, the result on the right shows the slope varying from 53,500 for liver to 21,400 for lung (2.5:1).

4 Discussion

The simulated time-resolved fluorescence signal provides us with a clear picture of how the excitation and emitted photons migrate in the medium. With the information of the photomigration time, one can simulate the amount of light which is absorbed within the turbid medium, using the proposed absorption correction method. As demonstrated with tissue-like phantoms in Fig. 4(b), the correlation between the corrected (intrinsic) fluorescence signal and the dye concentration has been dramatically improved by approximately 2000-fold in comparison to the uncorrected signal, when absorption of the phantoms was varied over a wide range (approximately by a factor of 30). However, the corrected correlation is not a perfect single line (about 30% over a wide range (approximately by a factor of 30)).

For the animal study, Fospeg® content ex vivo in murine organs was quantified. This drug contains the active ingredient m-THPC, and therefore is interesting as a PDT sensitizer. The observed signal level directly from the fluorescence imaging measurement is affected by many factors. It generally leads to a poor correlation between the signal level and drug concentration, as shown in Figs. 7(a) and 8(a). The fitted linear slope of the raw fluorescence signals at 652 nm varies drastically between different organs. The large variations in the raw signals indicate that absorption caused by tissue should be taken into account to allow quantification of the PS in the tissue samples. Tissue absorption at the interesting wavelengths is mostly dependent on the amount of hemoglobin (both oxy- and deoxy-hemoglobin) in the tissue. The high absorbance in lung, kidney, and liver is caused by high blood contents, attenuating both the excitation and emission light. This effect explains the lower slope of the correlation curves for these organs as compared to those for muscle and skin. The detailed selectivity and biodistribution of Fospeg® following systemic administration were studied separately in Ref. 31.

To compensate for the tissue absorbed light, the optical properties for different murine organs need to be known. Values from literatures vary a lot and seem not fully consistent between tissue types. The large variation in literature values results from the fact that measurements were performed on tissues from different species, in vitro or in vivo, and at a great variety of sample preparation techniques and other experimental conditions. In the preparation period of the tissue samples in this study, bleeding during organ removal caused partial loss of the blood resulting in a variation of absorption coefficient even for the same type of tissues. As mentioned above, we do not have the precise values of the tissue optical properties. Instead, the tabulated values from Ref. 23 were used. They could only be interpreted as reasonable but rough estimates of the true mouse tissue optical properties. This is one of the main reasons why the correlation is not as good as that for the phantom. The sensitivity of the correction factor to tissue absorption coefficients are also examined for the liver with highest absorption ($\mu_s^a = 26.5$ cm$^{-1}$, $\mu_m^a = 1.8$ cm$^{-1}$, $\mu_s^b = 11.5$ cm$^{-1}$, $\mu_m^b = 7.0$ cm$^{-1}$). In Table 5, the absorption coefficients have been altered by $\pm 30\%$, resulting in a variation in $\Delta$ from $-34\%$ to $+41\%$. Apparently this variation is less sensitive than that of the phantoms due to the much shorter migration pathlengths the photons spend in the epi-fluorescence geometry. Furthermore, if the tissue optical properties could be measured individually for each tissue investigated, simultaneously with the fluorescence imaging measurements, the correlation could be further improved.

The absorption correction method proposed in this study is based on assumptions that the fluorescent drug is homogeneously distributed within these tissues, and that all tissues have homogeneous optical properties. Unfortunately very little is known about distribution of this new drug following system-

### Table 2 Optical properties of different organs.

<table>
<thead>
<tr>
<th>Organs</th>
<th>$\mu_s^a$(cm$^{-1}$)</th>
<th>$\mu_m^a$(cm$^{-1}$)</th>
<th>$\mu_s^b$(cm$^{-1}$)</th>
<th>$\mu_m^b$(cm$^{-1}$)</th>
<th>$g^a = g^b(\cdot)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle</td>
<td>6.2</td>
<td>0.4</td>
<td>88.7</td>
<td>23.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Liver</td>
<td>26.5</td>
<td>1.8</td>
<td>57.5</td>
<td>34.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Kidney</td>
<td>4.9</td>
<td>0.3</td>
<td>240.9</td>
<td>117.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Lung</td>
<td>13.5</td>
<td>0.6</td>
<td>142.0</td>
<td>110.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

### Table 3 Sensitivity of the simulated correction factor to absorption coefficients of the phantoms.

<table>
<thead>
<tr>
<th></th>
<th>$\mu_s^a$, $\mu_m^a$</th>
<th>$\mu_s^a - 10%$, $\mu_m^a$</th>
<th>$\mu_s^a + 10%$, $\mu_m^a$</th>
<th>$\mu_s^b$, $\mu_m^b - 10%$</th>
<th>$\mu_s^b$, $\mu_m^b + 10%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variation in $\Delta$</td>
<td>0</td>
<td>$-23%$</td>
<td>$+26%$</td>
<td>$-27%$</td>
<td>$+32%$</td>
</tr>
</tbody>
</table>
Table 4  Sensitivity of the simulated correction factor to scattering coefficients of the phantoms.

<table>
<thead>
<tr>
<th>Variation in Δ</th>
<th>( {\mu'_s, \mu'_m} )</th>
<th>( {\mu'_s - 10%, \mu'_m} )</th>
<th>( {\mu'_s + 10%, \mu'_m} )</th>
<th>( {\mu'_s, \mu'_m - 10%} )</th>
<th>( {\mu'_s, \mu'_m + 10%} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>-22%</td>
<td>+25%</td>
<td>-18%</td>
<td>+19%</td>
</tr>
</tbody>
</table>

Table 5  Sensitivity of the simulated correction factor to absorption coefficients of murine livers.

<table>
<thead>
<tr>
<th>Variation in Δ</th>
<th>( {\mu'_s, \mu'_m} )</th>
<th>( {\mu'_s - 30%, \mu'_m} )</th>
<th>( {\mu'_s + 30%, \mu'_m} )</th>
<th>( {\mu'_s, \mu'_m - 30%} )</th>
<th>( {\mu'_s, \mu'_m + 30%} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>-34%</td>
<td>+41%</td>
<td>-10%</td>
<td>+9%</td>
</tr>
</tbody>
</table>
level. It is worthwhile to point out that the fluorophore lifetime does not influence the correlation in the model at all, since the absorbed light depends only on the photon migration time.

5 Conclusion

In conclusion, this paper has shown that the fluorescence imaging technique can be used as a noninvasive and sensitive tool to quantify the fluorescent markers in homogeneous turbid media, using the novel light-absorption correction approach combining the fluorescence imaging and FWMC simulations. The results on both the well-controlled tissue-like phantoms and ex vivo animal tissues have shown that this method provides an acceptable quantification of fluorescent molecule markers in media with known geometry and optical properties at both the excitation and emission wavelengths. An improved linear correlation with the true concentrations is obtained independent of the tissue optical properties, since this method efficiently compensates for light attenuation and thus more directly relates to the intrinsic fluorescence signal levels from the fluorophores. This approach offers the advantages of minimizing the dependence on the tissue optical properties, a very low concentration detection limit, and wide spectral bands. The sensitivity of the results to the medium optical properties variation are presented and discussed, in order to point toward the possible future improvement of this technique.

In future work, it is highly desirable to combine the sensitivity of the fluorescence imaging technique with the tissue optical properties measurements to constitute an even better and more reliable fluorophore concentration estimate. The absorption correction and image ratio methods could also be combined to compensate for tissue autofluorescence.

Acknowledgments

The authors are grateful to Biolitec AG for the realization of animal studies, HPLC analysis of tissue samples, and providing photosensitizer formulations (a drug they have a commercial interest in), and to Erik Alerstam for his assistance with the work carried out. This work was funded by the EU-Brighter project (FP6-IST-035266) and a Linneaus grant for the Lund Laser Center.

References


