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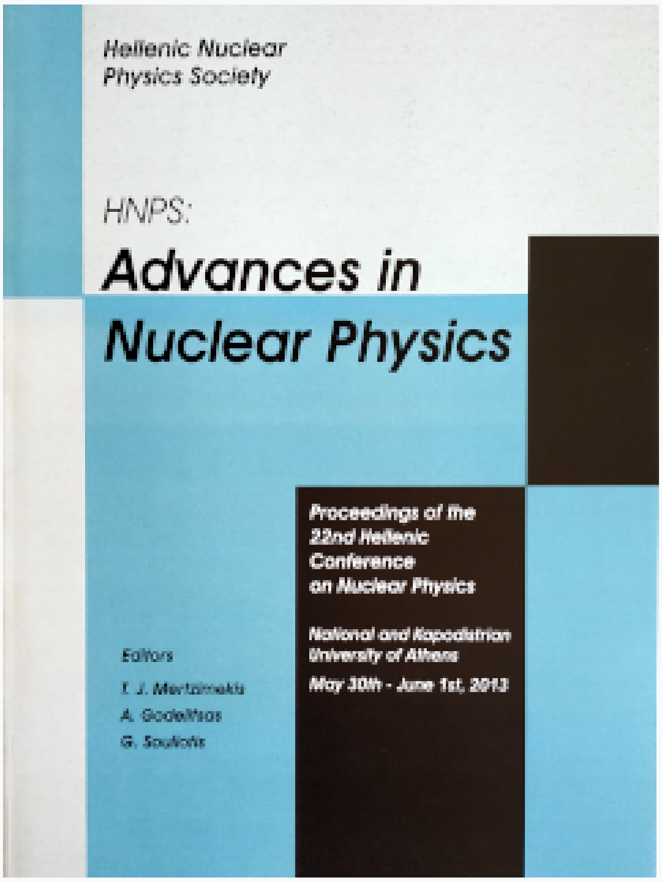

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Simulating a Time-Resolved Optical Tomographic Modality

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Abstract

The Single Photon Emission Computed Tomography (SPECT) using γ-radiotracers has been established as a standard technique in the physiological and functional Nuclear Imaging. However, anatomical information of the surrounding tissue structure is basically limited by this modality. Therefore, additional techniques, possibly non-ionizing, must be utilized in order to gain such knowledge. SPECT can be alternatively supported by adding a Time-Resolved Optical Tomographic (TROT) modality. The current work focuses on the feasibility of such a free-off ionizing, compact and low cost optical system. The architecture and the functionality of a time resolving optical construction, by means of a Monte-Carlo optical simulation, is presented in this study. An appropriate geometrical phantom is examined and a total of 24 projections covering the full angle region ($0^o - 360^o$) are obtained with this optical system. The planar information was further analyzed to reconstruct the tomographic images using Algebraic Reconstruction Techniques (ART). Obtained results from the simulation are presented and the system's efficiency, regarding spatial and time resolution, is discussed.

Keywords: Time-Resolved Optical Tomography (TROT), Monte-Carlo Optical Simulation, Tomographic Image Reconstruction

1. Introduction

The Single Photon Emission Computed Tomography (SPECT) is unambiguously a powerful, low cost diagnostic technique in modern medical practice. Nonetheless, one of its major drawbacks arises from the nature of the detected ionizing radiation, which makes impossible to obtain the anatomical information of the area under investigation without the assistance of another modality (X-ray CT, MRI, Ultrasound). The extra load of ionizing radiation (CT), the high cost (MRI) and also the mobility of such devises make those methods aggravating. A small-field γ-Camera system based on Position Sensitive Photomultipliers (PSPMT) has been already developed in our laboratory and also evaluated on a tomographic level [1]. Therefore, in order to gain the necessary anatomic information, a non invasive, non-ionizing, low cost and portable modality is proposed. This technique is based on the Time-Resolved Optical Tomography (TROT), well known for its absorbing and high-scattering physical nature. In the current study, it is attempted to simulate such a process for the limited case of small tissue thickness and low diffusivity and to apply the proper time filtering with respect to the ballistic light selection (early arriving photons), necessary for the reconstruction of the area under investigation.

2. Principle of Optical Imaging

Generally, two main processes are taking place when light propagates via tissues. Scattering, which is the dominant one, and absorption which is a secondary procedure. A very important step in optical imaging was

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the discovery of the "Physiological Window" which corresponds to Near-InfraRed (NIR) radiation at 650-950 nm (Figure 1) by Jöbsis in the late 1970s [2], where absorption is at a low proportion in relation with all other wavelengths. Therefore, photons of those wavelengths can travel several centimeters of tissue without absorption. As far as the scattering mechanism concerns, it has been proven that it is well approximated

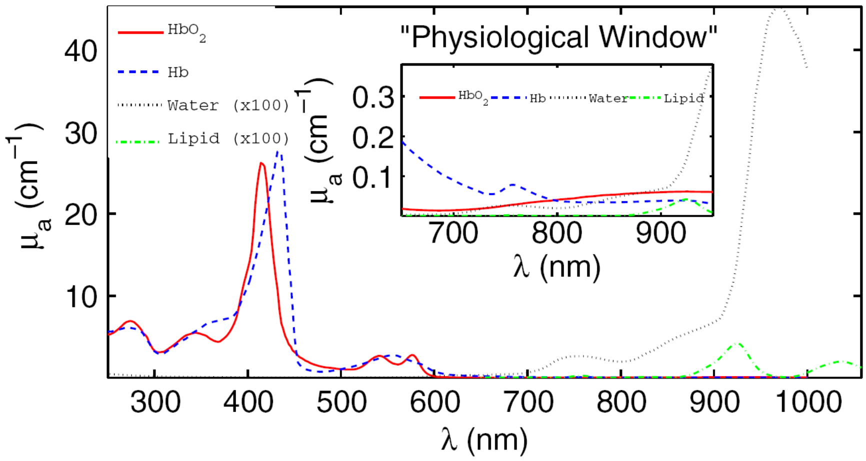

Figure 1: Absorption (μ_a) spectra of the tissue main components over the wavelength of photons. The inset represents the "Physiological Window". Here, as it is shown in Near InfraRed Spectroscopy (650-950 nm), the absorption by water, lipid and hemoglobin is in its lowest and light can travel several centimeters of tissue.

as a diffusive process. A model that separates the effects of tissue scattering from tissue absorption is required. The diffusion model provides a formal mathematical basis for this separation, and as a result of this approximation, experimenters can directly measure oxy- and deoxy-hemoglobin (HbO_2, Hbr/Hb), water and lipid concentrations using the well-known spectra of these molecules [3].

2.1. Time-Resolved Optical Imaging

It is possible to achieve X-ray-like imaging conditions, by utilizing NIR light from an Ultrafast LASER source (instead of ionizing radiation), even in a highly turbid medium like tissue. This can be achieved by using narrow-time pulsed light and proper time gating for the scattered photons which are propagating through the tissue as depicted in the left part of Figure 2. Consistently, if the early arriving photons

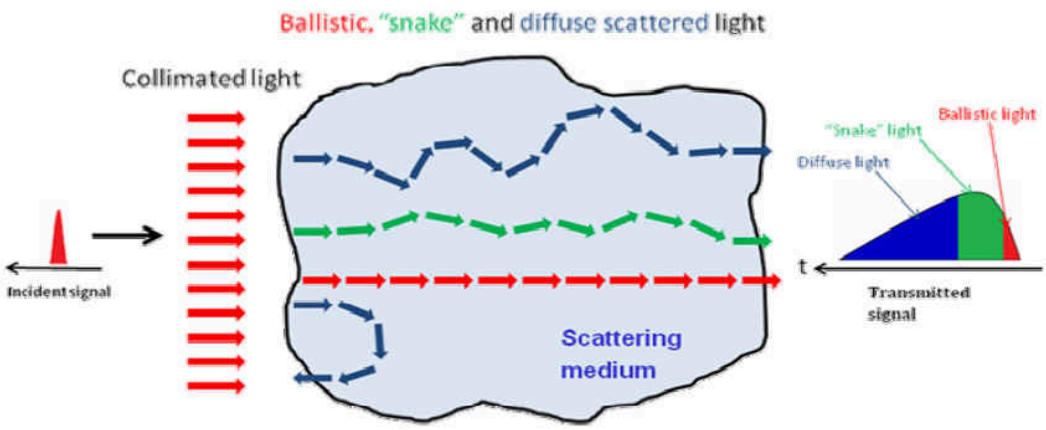

Figure 2: Near InfraRed pulsed light transmission through a scattering medium: (1) Earlier arriving Ballistic Light ($< 1ps$) with only diffraction-limited resolution (μm) (Red online) (2) Next arriving the Snake Light (<~100 ps) with a degraded resolution (10-100 μm) (Green) (3) Later arriving Diffused Light (>~100 ps) with a severely degraded resolution (cm) (Blue).

(unscattered photons), the so called *Ballistic Light*, can be isolated from the scattered light (*Snake* and *Diffused Light*), it is possible to gain the necessary information about the area of interest exactly like in the X-ray case. It is imperative at this point to understand that the duration of the incident pulse depends on the physical length of the medium under investigation. The shorter the path that light would follow, the sorter the pulse's duration must be.

A typical time distribution diagram for an Ultrafast LASER pulse at the InfraRed domain propagating through tissue (transmitted signal) is shown in the Figure 2. The early Ballistic Light arrives at times of the order of 1ps in contrast to the slightly scattered snake photons which dominate the $10-100$ ps range, followed by the later arriving diffused light at higher transition times (> 100 ps). In the first place, the duration of the detected pulse strongly depends on the physical length of the medium under investigation spreading over distance. Because the ballistic or snake photons are less scattered and transmit in the direction near the line connecting the source and detector, they can be separated from the scattered light by using time gating techniques described in the following section. The spatial resolution of the ballistic photons is only limited by diffraction effects (μm). The degraded resolution of the snake light corresponds to values of the order 10 to 100 μm.

2.2. Time Gating Techniques

Time gating is the collection of the early arriving photons by utilizing different physical procedures and methods. There is a variety of such techniques, nevertheless, the Streak Camera and the Kerr Gate techniques are the two most commonly used nowadays. The Streak Camera (Figure 3) is a device which operates by transforming the temporal profile of a light pulse into a spatial profile on a detector, by causing a time-varying deflection of the light across the width of the detector. In particular, a light pulse enters the instrument through a narrow slit along one direction. It then gets deflected in the perpendicular direction so that photons that arrive first hit the detector at a different position compared to photons that arrive later.

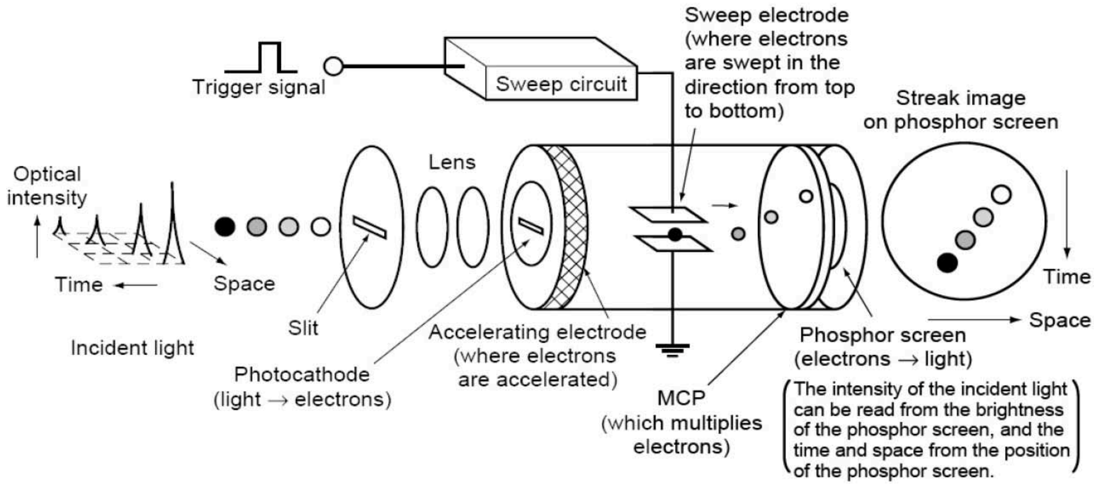

Figure 3: Streak Camera: Principle of Operation.

The Kerr Gate on the other hand uses the properties of certain materials such as Carbon disulfide which acts as an ultrafast shutter in the camera. It can be activated by an intense pulse which enables the crystal to "shut" like an iris of an aperture giving only few picoseconds to another photon pulse to pass through it and thus, allowing only the Ballistic Light to be collected. Of course, there are many other techniques referenced in the bibliography for time gating, such as the Optical Coherent Imaging, Holographic and Raman Scattering Methods as well as many Parametric Sum and Difference Frequency Generation Gates, which lie outside of the interest of the current study.

3. Monte-Carlo Simulation

The first logical step towards the operation study and design of a Time-Resolving Imaging prototype is the verification and the confirmation of the principles that would govern such an apparatus. Therefore, a simulation has to be performed in order to explore such properties, starting from an optimal case scenario (small tissue thickness and low diffusivity) and exploring more demanding schemes (thick tissues and high diffusivity). For this reason, a 3D phantom was designed using the DETECT2000 package [4], which is a Monte-Carlo simulator developed for the Computer Aided Design (CAD) of optical photon sensing devices and particularly for scintillation detectors. The DETECT2000 is a photon transport program which follows the fate of each generated photon in its passage through the various components and records the possible interactions (scattering, escape, absorption or detection) along its path. Besides the recorded path coordinates, the number of the encountered surfaces and the accumulated delay and elapsed time are also added to the detected information. Time analysis of the recorded photons can provide the required characteristic signal for appropriate selection of the Ballistic Light.

The phantom, consisting of five glass spheres (refraction index of n=2.15) in a cross formation with their centers laying on the same plane, was placed in an air cylinder as shown in Figure 4. Generated photons were propagated as a pulse from the left to the right base of the cylinder, passing and scattering also through the spheres. The pulse was consequently spread by the scattering in the medium and then recorded with all the above described information by the detective surface on the right. Accumulation of all detected photons forms the planar image shown in Figure 5. No absorption was taken into account in this simulation, assuming a well density controlled Near InfraRed radiation.

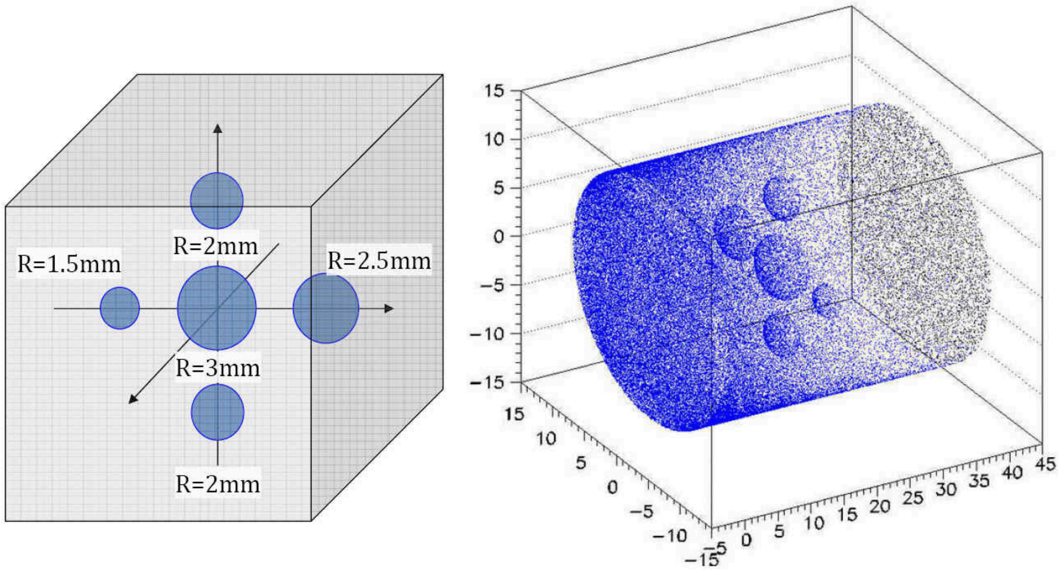

Figure 4: Geometry of the optical phantom with five refractive spheres in an air cylinder used in the Monte-Carlo simulation study with the DETECT2000 program. Absorbed and escaped photons during the simulation process are shown in the 3D plot. The light source is on the left side of the cylinder, while the detector resides on the right.

As it can be viewed in the Time-of-Flight diagram (Figure 5a), faster photons which arrive first at the detector surface show the fewer scatter occurrences (shorter optical path length) and form a sharp peak at the beginning of the detected time spectrum. The structure of this time distribution can be well understood in terms of multiple scattering events. Moreover, as expected, there is no information about the shape of the spheres on the timely non-gated image (Figure 5b). In order to gain such knowledge, it is logical to apply a proper time resolving cut to the detected photons and thus to achieve a kind of *filtering* on the planar information. To collect only the Ballistic Light, carefully selected time limitations have been successively

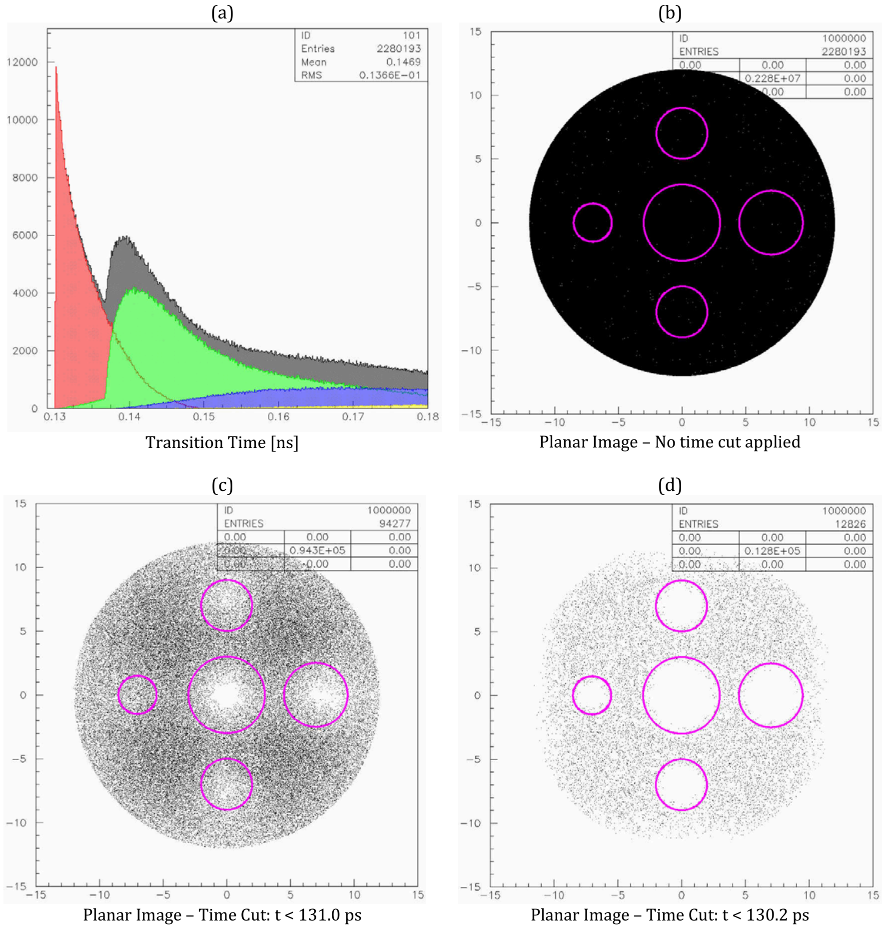

Figure 5: Detected photons after propagation through the sphere phantom. (a) Time of Flight of all the detected photons. Different colors indicate the number of scatter occurrences: Red (scattered twice), green (scattered three times), blue (scattered four times) and yellow (scattered five times). (b) The planar image before applying any time-cut as result of the detected photons. Indicated is also the expected positions and sizes of the phantom constituents. (c) Planar image obtained after applying a $t < 131.0$ ps time-cut to the data, which corresponds to the 4.1% of the total accumulated photons. (d) As previously, but with a $t < 130.2$ ps time-cut to the data, which corresponds to the 0.6% of the total accumulated photons.

assigned to this Time-of-Flight spectrum. Figures 5c and 5d show the derived planar information for two different time-cuts in the ballistic region. The first planar image (5c) is obtained after applying a $t < 131.0$ ps time-cut to the data, which corresponds to the 4.1% of the total accumulated photon statistics. Accordingly, the $t < 130.2$ ps time-cut to the data results to a clean planar image (5d) but with low statistics. Only the 0.6% of the total accumulated photons are carrying a practically usable phantom information. It is therefore obvious that strict time resolution criteria of the order of $1ps$ are unavoidable by the gating technique in order to successfully select the ballistic information and to obtain a clear projective image.

3.1. 2D and 3D Image Reconstruction

The Time Resolving Optical Tomography technique has been tested by generating planar images at different projection angles and by reconstructing the obtained information in a 2D and 3D image. As usually, 24 projections of the ballistic image were obtained by rotating the spheres phantom with a step of 15^o from 0^o to 360^o covering the full angle region. Afterwards, every projection was sliced along the symmetry axis (Z-axis) by taking into account the different time-cuts to reduce the background noise created by the late arriving photons. Tomograms for each level were produced by applying recursive reconstruction techniques like the Algebraic Reconstruction Technique (ART) with algorithms developed in our laboratory [5]. Finally, a 3D tomographic image is reconstructed using iso-surface interpolations within the MATLAB environment by stacking the created 2D slices at various Z-levels. An example of two tomograms at different Z-levels and the 3D-reconstruction of the spheres phantom is shown in Figure 6.

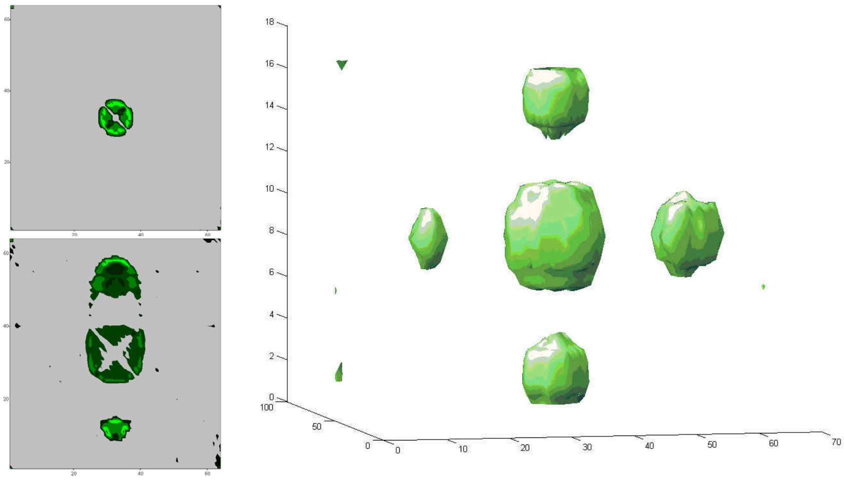

Figure 6: Left: Two tomograms at different z-levels. Right: 3D-reconstruction of the phantom by iso-surface interpolating the derived tomograms.

4. Concluding Remarks

The simulation study of an optical system by means of time resolving photon tomography using the DETECT2000 software package has been successfully performed. The optimal scenario of small tissue thickness and low diffusivity is simulated with a simple geometrical model. Proper time gating makes it possible to select the ballistic light and consequently to obtain planar images efficiently filtered and free of noise at the expense of the accumulated photon statistics. A tomographic image reconstruction process was performed with success in both 2D and 3D cases. Future plans include the expansion of the presented simulation techniques to more realistic phantoms and the investigation of the principle of operation with a fast photomultiplier and Ultrafast LASER pulses.

References

[1] M. Mikeli *et al.* "Sensitivity and Resolution Study of a Small-Field γ-Camera System on a Tomographic Level", IEEE Nuclear Science Symposium and Medical Imaging Conference Record M16-41 (2012) 3192–3195.
D. Thanasas *et al.* "A Correction Method of the Spatial Distortion in Planar Images from γ-Camera Systems", Journal of Instrumentation **4** (2009) P06012.
V. Spanoudaki *et al.* "Design and Development of a Position-Sensitive γ-Camera for SPECT Imaging based on PCI Electronics", Nucl. Instr. and Meth. **A 527** (2004) 151–156.

[2] F.F. Jöbsis: "Noninvasive Infrared Monitoring of Cerebral and Myocardial Sufficiency and Circulatory Parameters" Science **198** (1977) 1264–1267.
T. Durduran, R. Choe, W.B. Baker and A.G. Yodh: "Diffuse Optics for Tissue Monitoring and Tomography", Rep. Prog. Phys. **73** (2010) 076701.

[3] A. Yodh and B. Chance: "Spectroscopy and Imaging with Diffusing Light", Physics Today **48** (1995) 34–40.

[4] C. Moisan, F. Cayouet and G. McDonald: "DETECT2000: A Program for Modeling Optical Properties of Scintillators", Version 5, Laval University, Quebec, Canada (2000).

[5] S. Angeli and E. Stiliaris: "An Accelerated Algebraic Reconstruction Technique Based on the Newton-Raphson Scheme", IEEE Nuclear Science Symposium and Medical Imaging Conference Record M09-323 (2009) 3382–3387.