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# Spatial resolution and scanning time in the optical tomography of absorbing 'phantoms' under multiple scattering conditions

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**Abstract. Photon-counting optical tomography was used in the visualisation and projective reconstruction of the image of a strongly absorbing inclusion (a 'phantom'), 6 mm in diameter, hidden by multiple scattering processes in a model object (diameter 140 mm, absorption and scattering coefficients 0.005 and 1.4 mm$^{-1}$, respectively). It was demonstrated experimentally that when the probe radiation power was 10 – 13 mW the minimal (corresponding to the poorest signal/noise ratio $\sim$1) measurement time (photon-counting time) was 0.8 s per one measurement point and the total time needed to scan the whole object was less than 410 s.**

## 1. Introduction

One of the topical trends in modern medicine is the early diagnostics of diseases. Growth of this trend has become possible directly after the discovery of penetrating radiations, development of methods for detecting them, and studies of the processes of the interaction of such radiations with biotissues [1, 2]. The term 'tomography' has been adopted for the methods of visualisation of the internal structure of objects, which is inaccessible to direct observation [3, 4]. This task is usually carried out as follows: radiation is directed to a diagnostic object and this radiation then reaches a detection system. The characteristics of the detected radiation represent the initial data in what is known as the inverse problem [5] and the solution of this problem yields the distribution of a specific physical parameter which describes the absorption, scattering, conductivity, diffusion, etc. inside the diagnostic object [6 – 9].

The term 'optical tomography' is relatively recent. Since the radiation used in optical tomographs does not cause ionisation and its intensity does not as a rule exceed 10 – 100 mW mm$^{-2}$, optical tomography is regarded as noninvasive (the diagnostic object is weakly perturbed). Therefore, optical tomography is a very promising diagnostic method [10, 11]. An enormous number of publications on optical tomography have appeared so far [12 – 14] and many regular international conferences are being held [15 – 17].

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We recently described [18] a modulation (frequency-domain) optical tomograph (input radiation power 15 – 30 mW, modulation frequency 100 MHz) with a highly sensitive detection system based on the method of time-resolved photon counting. Our experiments on model objects (linear dimensions $D \leqslant 140$ mm, absorption and scattering coefficients $\mu_a = 0.005 - 0.015$ mm$^{-1}$ and $\mu_s = 1.4$ mm$^{-1}$, respectively) showed that the propagation of optical radiation under low-angle multiple scattering conditions [19, 20] can be described by a coefficient $\xi$ representing relative lengthening of the paths. The experimental values of $\xi$ depend on $\mu_a$ and lie in the range $\xi = 1.2 - 1.9$. Images of strongly absorbing inclusions ('phantoms'), which are cylinders $d = 10 -$ 23 mm in diameter, are reconstructed by a very fast (5 – 10 min) modification of the projection algorithm [5, 21] for solving the inverse problem. It has been suggested that under 'ideal' conditions there are practically no limitations on the spatial resolution of this optical tomography method. The smaller the dimensions of an absorbing phantom, whose image has to be reconstructed, the larger is the number of the projections required to solve the inverse problem (and the larger the dimensionality of the needed array of the initial experimental data) and the longer the time that has to be spent in the actual measurements (photon counting) to obtain one measurement point (for fixed positions of the radiation source and the photodetector) in order to ensure a reliable (exceeding the noise) detection of the phantom 'shadow'.

A rough estimate was obtained by us earlier [18] for the minimum measurement time needed to reconstruct the image of an absorbing phantom 5 mm in diameter located at the centre of a diagnostic object 140 mm in diameter and characterised by the scattering and absorption coefficients $\mu_s = 1.4$ mm$^{-1}$ and $\mu_a = 0.005$ mm$^{-1}$, respectively. This object simulated gray matter of the human brain [22]. It was found that the minimal measurement time for diametrically opposite positions of the radiation source and the photodetector (when the output signal was weakest) amounted to 45 s.

The purpose of the present investigation was to check experimentally the conclusions stated above and to obtain quantitative estimates. This involved real measurements on small phantoms, checking of the suitability of the algorithms described in Ref. [18] for an axially asymmetric geometry of the position of a phantom in the diagnostic object, and also an attempt to reduce the total scanning time by optimal utilisation of the symmetry of the problem geometry.

## 2. Experimental results

Our experiments were carried out on the prototype tomograph described in Ref. [18]. Our model object was a cylindrical container 140 mm in diameter. Its perimeter was divided into 32 equal angular intervals by holes for input and output single-core (core diameter 600 μm) plastic optical fibres. The probe radiation power from a cw laser diode ($\lambda = 775$ nm) was 10 – 13 mW. The container was filled with a model medium which was a mixture of two components. The first component (water solution of ink) was the pure absorber ($\mu_s = 0$) and the second component (water emulsion of fat) was the scatterer ($\mu_a = 0$). Black metal cylinders with a diameter up to 6 mm were the strongly absorbing phantoms, simulating hematomas. The phantom images were reconstructed from the experimental data by means of the algorithms and programs described in Ref. [18].

The experimental results on the visualisation of an absorbing phantom, $d = 6$ mm in diameter, placed at the centre of an object, $D = 140$ mm in diameter and characterised by $\mu_s = 1.4$ mm$^{-1}$ and $\mu_a = 0.005$ mm$^{-1}$, are illustrated in Fig. 1. We can easily see that the 'shadow' region is recorded very reliably (with the signal/noise ratio $\approx 15$) when the counting time per one measurement point is 180 s. In the absence of a phantom the experimental dependence of the number of photocounts $N$ on the distance $L = D\sin(\alpha/2)$ between the radiation source and the photodetector can be approximated by the function [18]

$$N(L) \propto L^{-2}\exp(-\mu_a \xi L) \qquad (1)$$

and this gives $\xi = 2.1 \pm 0.3$, in agreement with the results reported in Ref. [18]. Here, $\alpha$ is the central angle between the radiation source and photodetector positions. In reconstructing the phantom image the experimental data were first smoothed out and shifted angularly. The diameter of the reconstructed image of a phantom was 6.7 mm (Fig. 2). The experimental results yielded estimates of the minimal (for the worst signal/noise ratio $\sim 1$) time needed to obtain one measurement point and of the total scanning time, which were 0.8 and 25.6 s, respectively.

Figs 3 and 4 give the experimental results on the visualisation of a phantom, $d = 25$ mm in diameter and shifted from the centre of the object, when the parameters of the model medium were the same as in Fig. 1. In this experiment the diagnostic object was fully scanned at 32 possible

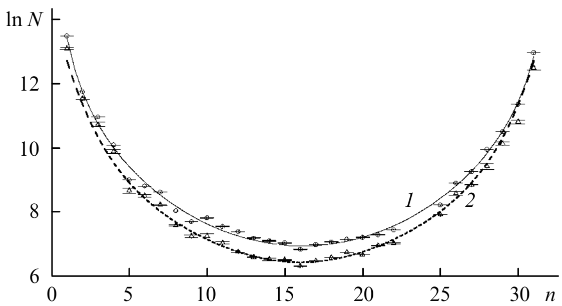


**Figure 1.** Dependences of the number of photocounts $N$ on the position (number $n$) of the output optical fibre in the absence (*1*) and in the presence (*2*) of a phantom when the object and phantom diameters were 140 and 6 mm, respectively ($\mu_a = 0.005$ and $\mu_s = 1.4$ mm$^{-1}$). The radiation was coupled in by an optical fibre at the position $n = 0$.

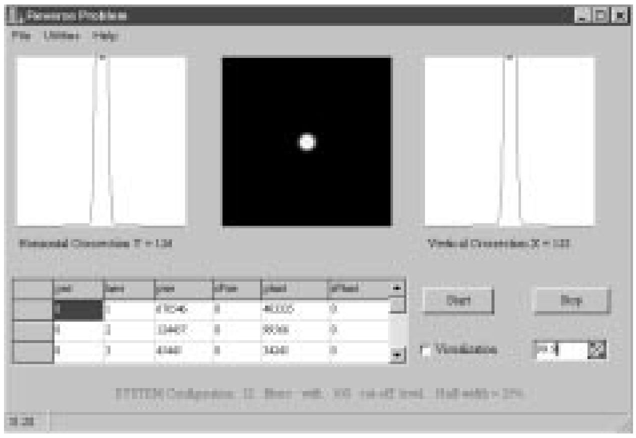

**Figure 2.** Reconstructed image of a totally absorbing phantom (central window) and transverse sections of the absorption coefficient distributions (right and left windows) obtained for an object and a phantom of diameters 140 and 6 mm, respectively ($\mu_a = 0.005$ and $\mu_s = 1.4$ mm$^{-1}$).

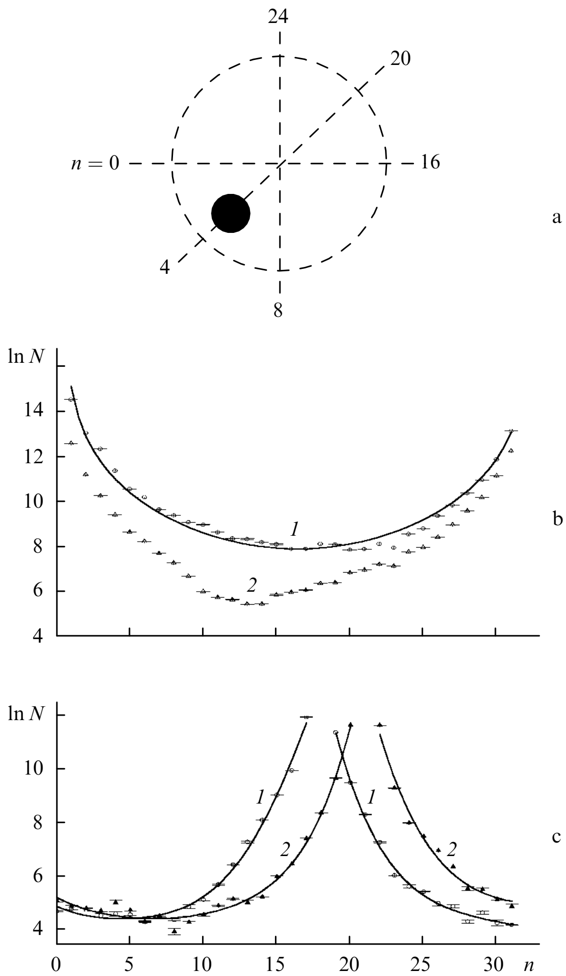


**Figure 3.** Experimental geometry (a) and dependences of the number of photocounts $N$ on the position (number $n$) of the output optical fibre (b, c) obtained for the object and phantom diameters 140 and 6 mm, respectively ($\mu_a = 0.005$ and $\mu_s = 1.4$ mm$^{-1}$). The radiation was coupled in through an optical fibre at the position $n = 10$ in the absence (*1*) and presence (*2*) of a phantom (b) and through optical fibres at the positions $n = 18$ (*1*) or $n = 21$ (*2*) in the presence of a phantom (c).

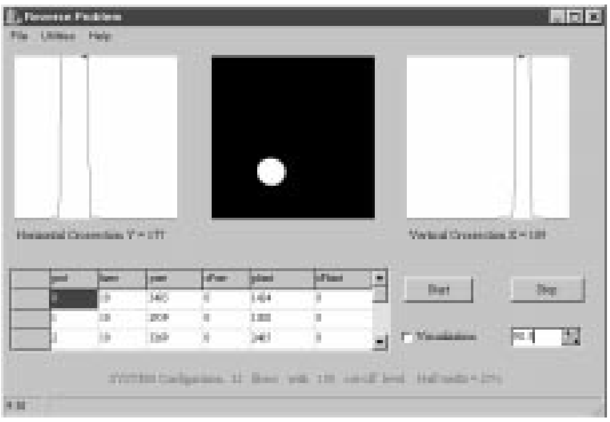

**Figure 4.** Reconstructed image of a totally absorbing phantom (central window), shifted from the centre of the object, and transverse sections of the absorption coefficient distributions (right and left windows) for the object and phantom diameters 140 and 25 mm, respectively ($\mu_a = 0.005$ and $\mu_s = 1.4$ mm$^{-1}$).

positions of the radiation source. All the experimental dependences revealed clearly the 'shadow' regions whose positions, dimensions, and shapes varied with the position of the radiation source (Figs 3b and 3c). Nevertheless, a definite and fully evident symmetry was retained in the task of reconstructing the image of the shifted phantom. It could be demonstrated easily that displacement of the radiation source symmetrically relative to the axis passing through the centres of the object and phantom simply shifted and specularly symmetrically inverted (relative to the abscissa axis) the corresponding experimental dependences (Fig. 3c). This made it possible to halve the scanning time. The experimental results made it easy to visualise the image of the shifted phantom (Fig. 4). Bearing in mind the symmetry of the problem in visualisation of the phantom, $d = 6$ mm in diameter and shifted from the centre of the diagnostic object, we estimated that complete scanning of the object would require no more than 410 s (for the worst signal/noise ratio $\sim 1$). The scanning time could be reduced significantly by multichannel detection of the output signal.

## 3. Conclusions

Optical tomography was used in visualisation and projective reconstruction of the image of a strongly absorbing inclusion (a phantom 6 mm in diameter) when this phantom was hidden by the processes of multiple scattering in a model object (140 mm in diameter, absorption and scattering coefficients 0.005 and 1.4 mm$^{-1}$). The experiments reported above confirmed our earlier conclusion [18] that there are no fundamental limitations on the spatial resolution in the visualisation of absorbing phantoms by optical tomography: smaller phantoms can be visualised simply by increasing the measurement time and the number of projections (the dimensionality of the array of the initial experimental data should be large). It was found experimentally that for a laser diode power of 10–13 mW the minimal (corresponding to the worst signal/noise ratio $\sim 1$) measurement time was about 0.8 s per one point and the time needed for complete scanning of the object did not exceed 410 s, which would be fully acceptable in many practical applications. However, even this time could be reduced significantly by the use of multichannel photodetectors such as CCD linear or two-dimensional arrays. The experimental coefficient representing the relative lengthening of the paths was found to be $\xi = 2.1 \pm 0.3$.

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