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Application of Fluorescent PSF for 3D Reconstruction of Absorbing Structure using Slab Transillumination Images*

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Abstract— **In transillumination imaging of an animal body using near-infrared light, the image is blurred due to the strong scattering in the tissue. We have devised the depth-dependent point spread function (PSF) to suppress the scattering effect in fluorescent imaging. In this study, we applied this principle and developed a technique to reconstruct the absorbing structure in turbid medium without using fluorescent material. In experiments, the feasibility and effectiveness of the proposed technique were verified.**

I. Introduction

The transillumination imaging using near-infrared light (NIR) is a promising technique for noninvasive imaging of an animal body. However, it has not been widely used in practical applications. The transillumination image is blurred due to the strong scattering effect in the tissue. This image blurring can be considered as the convolution of a point spread function (PSF) of the scattering medium. If we can obtain an appropriate PSF, we can suppress the scattering effect by the deconvolution with the PSF. To restore the clear image of a fluorescent source, we have devised the depth-dependent PSF to suppress the scattering effect in fluorescent imaging. In this study, we applied this principle and developed a technique to reconstruct the absorbing structure in turbid medium without using fluorescent material.

With the 2D NIR transillumination images from different orientations, we can expect to realize 3D optical CT of an animal body. As the first step for the 3D imaging, we have conducted a basic study to examine the feasibility of this methodology. The effectiveness of the proposed technique was also examined in experiments using the tissue-equivalent phantom with a known internal absorbing structure.

II. Scattering Suppression by PSF Deconvolution

A. PSF for Fluorescent Source

In previous study [1-3], the depth-dependent PSF was derived to describe the blurring phenomena by scattering for a fluorescent point source in a slab scattering medium. This PSF was calculated on the assumption that the surface of scattering medium was flat. With a point source of light, the spatial distribution of light intensity is given by,

$$PSF(\rho) = \frac{3P_0}{(4\pi)^2}\left\{(\mu'_s + \mu_a) + \left[\kappa_d + \frac{1}{(\rho^2+d^2)^{1/2}}\right] \times \frac{d}{(\rho^2+d^2)^{1/2}}\right\} \frac{\exp\left[-\kappa_d(\rho^2+d^2)^{1/2}\right]}{(\rho^2+d^2)^{1/2}}, \quad (1)$$

where $\kappa_d = \sqrt{3\mu_a(\mu'_s+\mu_a)}$, P_0, μ'_s, μ_a, d and ρ are the optical power of a point source, the reduced scattering coefficient, the absorption coefficient, the depth of a point source, and the radical distance in the cylindrical coordinate system respectively.

B. Applicability of Source PSF to Absorption

In transillumination imaging of an absorbing structure, the homogeneous light is irradiated from outside the scattering medium. The scattered light goes through the absorbing structure and projects the shadow on the surface of the scattering object.

If the light is diffused well at the depth of the absorbing structure, we can consider that the absorbing structure as a set of light point sources. Then, we can consider that the PSF for the light source is applicable to the transillumination images of an absorbing structure.

The above applicability was examined in an experiment. Fig. 1 shows the experimental system. As scattering medium, an Intralipid suspension was mixed with distilled water and black ink to make a tissue-equivalent medium (μ'_s = 1.0 /mm, μ_a = 0.01 /mm). As an absorbing structure, a black-painted metal plate (20 × 100 × 1 mm^3) was used. This absorber was placed in an acrylic container (40 × 100 × 100 mm^3) filled with scattering medium. The depth of the absorber from the observation surface can be varied from 2 to 15 mm. This phantom is irradiated with the NIR light from a laser (Ti:Sapphire, 800 nm wavelength) through a beam expander for homogeneous illumination. Image is captured using a cooled CCD camera placed at the opposite side of the phantom to the light incident side.

We first obtained transillumination image $f_o(x, y)$ of an absorbing object in a transparent medium, or clear water. Then, we replaced the water with the scattering medium, and obtained the transillumination image $f_s(x, y)$. The point spread function for the absorbing structure $PSF_{abs}(x, y)$ was calculated as,

$$PSF_{abs}(x, y) = f_s(x, y) \circledast f_o(x, y), \quad (2)$$

where $\circledast$ denotes the deconvolution.

The measured $PSF_{abs}(x, y)$ was compared with the theoretical PSF of the fluorescent source or (1) using the same

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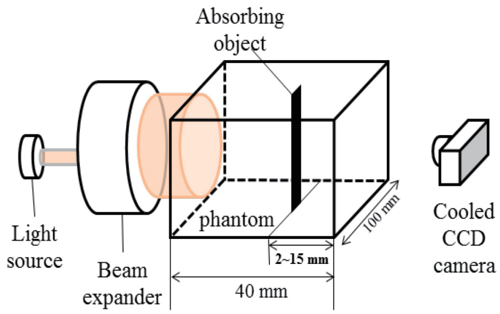


Figure 1. Experimental setup for transillumination imaging.

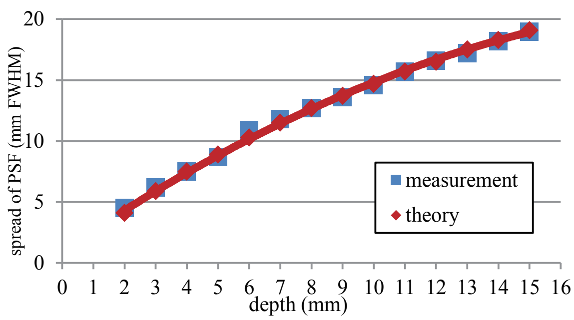


Figure 2. Comparison of spread of PSF between theoretical PSF for light source and measured PSF for absorber.

conditions of the experiment. Fig. 2 shows the result of comparison in terms of the full width at half maximum (FWHM) of these two PSFs. At the same depth d, both PSFs were found to be in good agreement.

Through this analysis, it was verified that the depth-dependent PSF for the fluorescent light source is applicable to the transillumination images of absorbing structure.

C. *Experimental Verification of Scattering Suppression*

The effectiveness of the PSF_{abs} to suppress scattering effect in a transillumination image was examined in an experiment. A Y-shape black tube (3 mm in diameter) was placed at 5 mm depth from the observation surface. Figs. 3(a) and 3(b) show the observed transillumination image and the result of deconvolution with PSF_{abs}. The separation of Y-shaped arms became clear by the deconvolution with an appropriate PSF. We can see the effectiveness in the intensity profiles shown in Fig. 3(c), as well.

Through this experimental analysis, it was confirmed that the PSF derived for a fluorescent light source is applicable and effective for suppress the scattering effect in transillumination images.

III. DECONVOLUTION FOR DEEP ABSORBER

When an absorbing structure is deep in a turbid medium, the width of PSF becomes large. Then, the deconvolution requires much iterative calculation and result tends to be unstable. To overcome this difficulty, we devised a technique to divide the PSF into multiple pieces, i.e.

$$PSF(\rho) = PSF_{part}(\rho) * PSF_{part}(\rho) * \ldots * PSF_{part}(\rho),$$
$$\text{where } PSF_{part}(\rho) = \mathcal{F}^{-1}\left[\{\mathcal{F}[PSF(\rho)]\}^{1/n}\right] \quad (3)$$

where ∗ denotes the convolution.

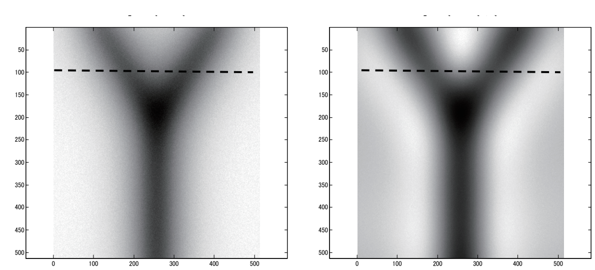
In this way, the n times deconvolution with $PSF_{part}(\rho)$ becomes equivalent to the one time deconvolution with $PSF(\rho)$. As the division number n increases, the width of $PSF_{part}(\rho)$ becomes less, and the deconvolution process becomes stable.

The validity of this technique was examined in an experiment. The same absorber as that in Fig. 3 was placed at 10 mm depth from the observation surface of the turbid medium. Fig. 4(a) shows the observed transillumination image. Due to the strong scattering effect, the shape of the absorber was difficult to recognize. Figs. 4(b) and 4(c) show the results of the one-time deconvolution with $PSF(\rho)$ and the three-times deconvolution with $PSF_{part}(\rho)$. The Y-shape structure became recognizable by the deconvolution. The better performance with the $PSF_{part}(\rho)$ could be seen in these figures and the intensity profiles in Fig. 4(d), as well.

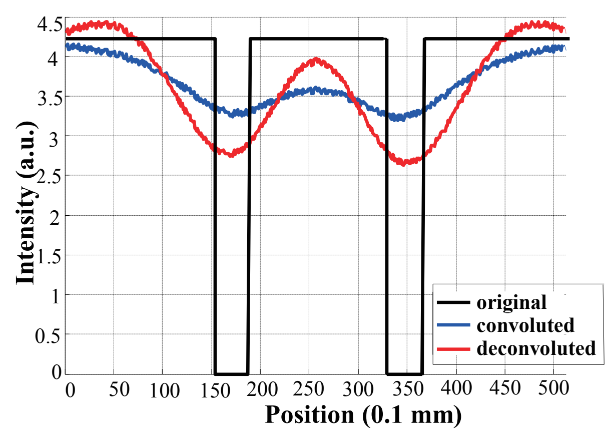
In this analysis, it was confirmed that we can suppress the severe scattering effect in transillumination image, even when the absorbing structure is deep from the observation surface.

IV. 3D RECONSTRUCTION

The transillumination image deteriorated by scattering can be significantly improved using appropriate PSFs. When we obtain these images from many circumferential directions, they can be the projection images for the computed tomography (CT). Therefore, using the filtered back projection (FBP) algorithm, we can expect the three dimensional (3D) reconstruction of the absorbing structure in a turbid medium.

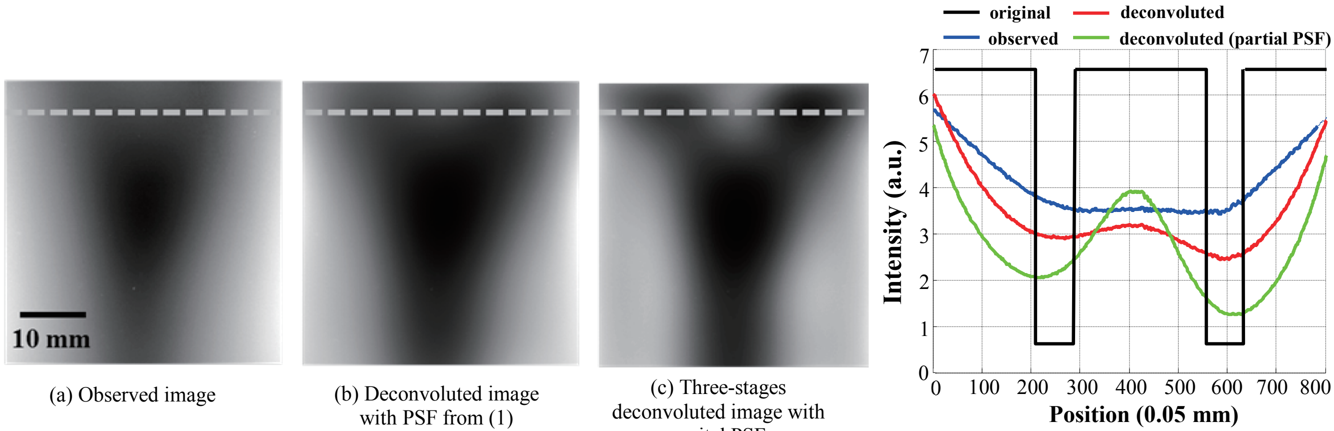


(a) Observed (b) Deconvoluted



(c) Intensity profiles

Figure 3. Transillumination image.



(a) Observed image

(b) Deconvoluted image with PSF from (1)

(c) Three-stages deconvoluted image with parital PSF

(d) Intensity profiles

Figure 4. Deconvolution of observed transillumination images.

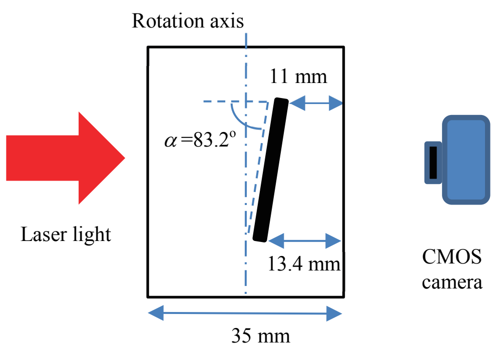


Figure 5. The side view of phantom model

The feasibility of the 3D reconstruction was examined in an experiment. Fig. 5 shows the target structure of this experiment. A slant cylindrical post (3 mm in diameter, 20.25 mm in length) was fixed in the rectangular container filled with the scattering medium with tissue-equivalent optical parameters (μ'_s = 1.0 /mm, μ_a = 0.00536 /mm). Laser light (Ti:Sapphire, 850 nm wavelength) was illuminated from one side of the container and the transillumination image was recorded with a cooled CMOS camera from another side of the container. This recording was repeated while rotating the absorber post around the rotation axis in the figure using a mechanical rotation system.

In this case, the depth of the absorber was not constant along the vertical axis. Thus, the PSF's with different depths were applied to a transillumination image, and horizontal intensity profiles were extracted at the proper vertical heights in the improved image obtained by the proper PSF with the correct depth. This horizontal intensity profiles were obtained from different circumferential orientations, and the cross-sectional image was reconstructed using the FBP algorithm. Finally, we piled up the cross-sectional images along the vertical axis, and reconstructed the 3D structure. In the PSF deconvolution, the partial PSF's were used.

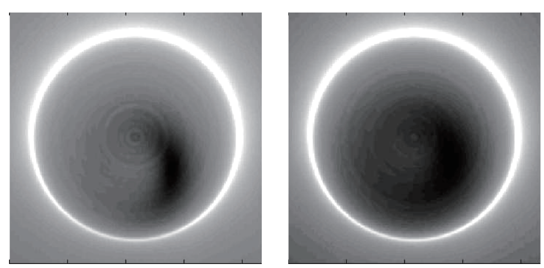
Fig. 6 shows the observed transillumination image and the result of the partial PSF deconvolution. In this case, the absorbing post was parallel to the observation surface, and we could use the PSF with a single depth. The observed image was severely deteriorated by the effect of strong scattering. Its effect was greatly suppressed by the proposed technique.

Fig. 7 shows the cross-sectional image reconstructed from the observed transillumination images. The position of the absorber was difficult to identify. Fig. 8 shows the

(a) Observed image

(b) Deconvoluted image

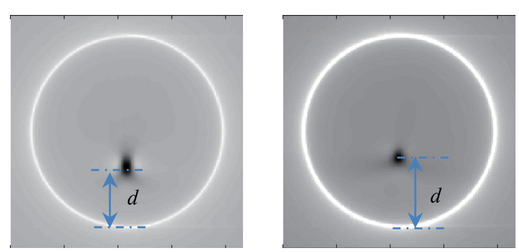
Figure 6. The observed and deconvoluted images of absorber.



(a) Top of absorber

(b) Bottom of absorber

Figure 7. Cross sectional images of reconstructed from observed images.



(a) Top of absorber
restored d = 10.14 mm
given d = 11 mm

(b) Bottom of absorber
restored d = 12.6 mm
given d = 13.4 mm

Figure 8. Cross sectional images of reconstructed from deconvoluted images.

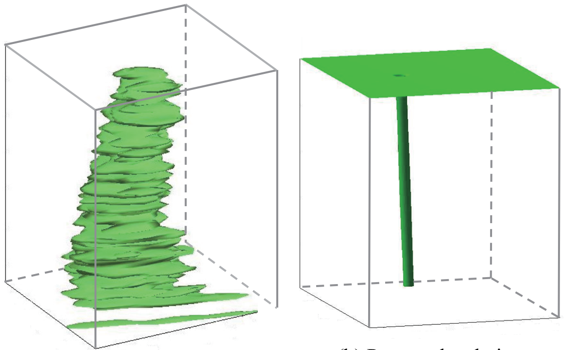


Figure 9. 3D Reconstruction of absorbetr in turbid medium.

cross-sectional image reconstruction by the proposed technique. The position of the absorber was clearly identified. The reconstruction error was 6~8%.

Fig. 9 shows the result of the 3D reconstruction. The absorbing structure in tissue-equivalent turbid medium was clearly reconstructed by the proposed technique.

In the above reconstruction the depth parameter of the PSF was given as a known value. If there is no information on the depth of the absorbing structure beforehand, we apply the depth estimation techniques [2] first and apply the proposed technique.

V. Conclusion

With a view toward the reconstruction of the absorbing structure in turbid medium, a fundamental study was conducted. The applicability of the PSF for a fluorescent light source to an absorbing structure was verified. We proposed a scattering suppression technique using piece-wise partial PSF deconvolution. The effectiveness was confirmed in experiments.

With these 2D images obtained with our scattering suppression technique, the 3D reconstruction of the absorbing structure could be reconstructed. These results suggest the possibility of the optical 3D imaging of internal structure in animal experiments and clinical applications.

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