High-contrast and noise-robust image reconstruction with regularization minimizing entropy for diffuse optical tomography

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論文題目

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論文の内容の要旨

[Introduction]

Diffuse optical tomography (DOT) is an emerging non-invasive imaging technique that utilizes near-infrared light to provide spatial distribution of intrinsic optical properties (i.e., scattering and absorption coefficients) of tissues. Light illuminated on tissue surface is scattered and absorbed by biological tissues, and a portion of the scattered light is detected at multiple positions of the tissue surface. DOT image is reconstructed by minimizing the difference between the measurements and the theoretical predictions based on the mathematical models, such as the radiative transfer equation and the photon diffusion equation (PDE), describing the light propagation. Main clinical applications of DOT are functional brain imaging and cancer detection such as breast and thyroid cancers, in which light absorption can be changed by changes in hemodynamics and vascularity. The high spatial resolution of DOT is challenging due to an inherently ill-posed inverse problem.

To overcome this issue, regularization techniques are employed. Although l_1-norm regularization has been reported to improve the image contrast, the reconstructed images are contaminated by artifacts arising from measurement noise. In this study, a regularization method that minimizes entropy of the reconstructed image was proposed to improve the contrast and noise robustness. We demonstrated the performance of the entropy regularization as compared to the l_1-norm and l_2-norm regularizations in numerical simulations and a phantom experiment.

[Methods]

Numerical simulations, where the time-dependent PDE was solved with the finite element method, were performed on a 2D circular object with a radius of 40 mm, at which 16 co-axial optical fibers were attached. At a time, the one of the 16 optical fibers illuminated the object and the other 15 optical fibers detected the light. As a result, we obtained 240 distributions of photon time-of-flight (DTOFs), from which mean time of flights (MTFs) were calculated and used for image reconstruction. We set the reduced scattering coefficient μ_s' = 0.8 mm^{-1} and the absorption coefficient μ_a = 0.007 mm^{-1} in the background of the medium. In the numerical simulations, 4 cases were considered. Case (1) includes 2 targets with a radius of 5 mm which equally had μ_a = 0.014 mm^{-1}. The distance of the targets’ centers was 20 mm. Case (2) includes a single target with a radius of 10 mm and μ_a = 0.014 mm^{-1}. The contrast and noise-robustness of the reconstructed images were examined in cases (1) and (2). Case (3) includes a single target with a radius of 10 mm and $\mu_a = 0.028$ mm^{-1}, while in case (4), a single target with a radius of 5 mm and $\mu_a = 0.014$ mm^{-1} was used. In cases (3) and (4), the effects of target contrast and size on the regularization parameter (λ) were studied.

In a phantom experiment, the phantom made from polyacetal resin, of which height and radius were 240 mm and 40 mm, respectively, was used. The phantom had a cylindrical hole of radius 10 mm filled with Intralipid of which μ_s' was 1.05 mm^{-1} and μ_a was 0.0026 mm^{-1}. The time-domain measurement system consisted of 3 pulsed laser diodes, coaxial optical fibers, photomultiplier tubes and time correlated single photon counting systems. The illumination and detection were carried out in the same manner in the numerical simulations.

[Results and discussions]

In the numerical simulation case (1), we confirmed that entropy regularization improved the contrast of the reconstructed target. The entropy regularization reconstructed the target with 105% of true changes in μ_a value, while the l_1- and l_2-norm regularizations reconstructed 60% and 10%, respectively. The reconstructed area of the targets by the entropy regularization was closer to the true one than those for the l_1-norm and l_2-norm regularizations. The entropy regularization suppressed artifacts and distortion due to noise more robustly. In case (2), the improvement in the contrast was confirmed similarly to case (1). In case (3), when λ was 3×10^{-2}, the target was reconstructed most correctly (108% of the true μ_a value). On the other hand, in case (4), λ provided the best estimation was merely different from the that in case (2). As a result, the effect of the target contrast on λ was more significant.

In the phantom experiment, the entropy regularization provided the image with higher contrast as well as in the numerical simulations. In image reconstruction with the entropy regularization, the peak value of μ_a was 5 times and 16 times larger than those with the l_1- and l_2- norm regularizations, respectively. Whereas mismatch in the 2D image reconstruction for the 3D measurement and the crosstalk between μ_s' and μ_a of Intralipid caused the error in reconstructed peaks. The reconstructed area with the entropy regularization was more similar to the true target area than those with the l_1-norm and l_2-norm regularizations. However, the negative artifacts were observed in the image reconstructed with the entropy regularization.

[Conclusions]

In both the numerical simulations and the phantom experiment, the entropy regularization consistently was better than the l_1-norm and l_2-norm regularizations by enhancing contrast and lowering effects of noise. The entropy regularization was effective in suppressing measurement noises, preserving important image structures at high contrast. Employment of the entropy regularization can improve the quality of the DOT.