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A Gradient-based inversion scheme including spatial constraints for reconstruction of the absorption, diffusion and Grueneisen coefficients in multiple illumination photoacoustic tomography

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Abstract: By considering photoacoustic measurements normalized to one reference, the resulting normalized signal is not depending on the acoustic properties of the medium and uncoupled reconstructions of the optical and acoustic (Grueneisen coefficient) parameters are obtained.

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1. Introduction

In photoacoustic tomography (PAT), the uncoupled optical properties (absorption and diffusion coefficients) are obtained with an inversion process that is usually divided into two steps that are, most of the time, solved sequentially: the first step is the resolution of the initial boundary problem to obtain the initial pressure distribution, the second one is devoted to the reconstruction of the optical parameters, knowing the Grueneisen coefficient. With multiple source illuminations, uncoupled reconstructions of the three desired parameters can be obtained. Reconstructing Γ offers also the possibility to monitor modifications in mechanical and thermodynamical properties of the tissues (speed of sound, temperature). Shao et al. [1] have developed a semi-analytical approach with a linear formulation of the optical properties inverse problem that allows to recover them independently. Here, we propose a gradient-based reconstruction scheme that allows to recover these coefficients non linearly. Moreover, our group [2] has proposed a method to help the localization of biological abnormalities in tissues, such as cancers, that present most of the time a dual optical and acoustic contrast. The signatures of these contrasts are present in the measured photoacoustic signal, and can be exploited to build a map of probability of presence of such abnormalities. This map can be included in the reconstruction algorithm as a spatial prior knowledge.

2. Gradient-based formulation

Let's consider S multiple source illumination measurements such that S different initial pressure distribution maps $p_s(\mathbf{r})$, $s \in [1, S]$, can be obtained (inversion of the acoustic pressure wave equation):

$$p_s(\mathbf{r}) = \Gamma(\mathbf{r})\mu_a(\mathbf{r})\phi_s(\mu_a(\mathbf{r}), D(\mathbf{r})), s \in [1, S], \quad (1)$$

where $\Gamma(\mathbf{r})$ is the Grueneisen coefficient [-], $\mu_a(\mathbf{r})$ and $D(\mathbf{r})$ are respectively the absorption ($[\text{cm}^{-1}]$) and the diffusion ($[\text{cm}]$) coefficients, and ϕ_s is the fluence ($[\text{J}\cdot\text{cm}^{-2}]$), for source number s , $s \in [1, S]$. One of the measurements $i \in [1, S]$ can be chosen as the reference measurement, preferentially one having a good signal to noise ratio. One can then consider as the new measurable quantities, the following normalized initial pressures:

$$M_s(\mathbf{r}) = \frac{p_{s,s \neq i}(\mathbf{r})}{p_i(\mathbf{r})} = \frac{\phi_{s,s \neq i}(\mu_a(\mathbf{r}), D(\mathbf{r}))}{\phi_i(\mu_a(\mathbf{r}), D(\mathbf{r}))}. \quad (2)$$

A minimization based approach has been formulated for the resolution of the inverse problem, in which it is sought to find $(\mu_a(\mathbf{r}), D(\mathbf{r}))$ which minimizes the error functional:

$$F = \frac{1}{2} \sum_s \int_{\Omega} (M_s^m(\mathbf{r}) - M_s(\mu_a(\mathbf{r}), D(\mathbf{r})))^2 d\mathbf{r}, \quad (3)$$

where M_s^m is the normalized measured initial pressure distribution map due to source s . The gradients of F with respect to the optical parameters μ_a and D are derived and can be expressed as:

$$\begin{aligned}\nabla F_{\mu_a} &= \sum_{s=1}^S \phi_s \phi_s^*, \\ \nabla F_D &= - \sum_{s=1}^S \nabla \phi_s \cdot \nabla \phi_s^*,\end{aligned}\quad (4)$$

where $\phi_s, s \in [1, S]$, are solutions to the diffusion equation:

$$\mu_a(\mathbf{r})\phi_s(\mathbf{r}) - \nabla \cdot (D(\mathbf{r})\nabla \phi_s(\mathbf{r})) = S_s(\mathbf{r}), \quad (5)$$

and ϕ_i^* and ϕ_s^* are solutions to the two following adjoint problems:

$$\begin{aligned}\mu_a(\mathbf{r})\phi_i^*(\mathbf{r}) - \nabla \cdot (D(\mathbf{r})\nabla \phi_i^*(\mathbf{r})) &= \frac{\phi_s(\mathbf{r})}{\phi_i^2(\mathbf{r})} (M_s^m(\mathbf{r}) - M_s(\mu_a(\mathbf{r}), D(\mathbf{r}))), \\ \mu_a(\mathbf{r})\phi_s^*(\mathbf{r}) - \nabla \cdot (D(\mathbf{r})\nabla \phi_s^*(\mathbf{r})) &= -\frac{1}{\phi_i(\mathbf{r})} (M_s^m(\mathbf{r}) - M_s(\mu_a(\mathbf{r}), D(\mathbf{r}))), s \neq i,\end{aligned}\quad (6)$$

Once the optical parameters are reconstructed, the Gueneisen coefficient can be estimated as:

$$\Gamma(\mathbf{r}) = \frac{\sum_{s=1}^S p_s^m(\mathbf{r})}{\mu_a(\mathbf{r}) \sum_{s=1}^S \phi_s(\mu_a(\mathbf{r}), D(\mathbf{r}))}, \quad (7)$$

where p_s^m is the measured initial pressure distribution map due to source s . A regularization parameter can be added to stabilize the reconstructions.

3. Conclusion

Hence, within a non linear iterative reconstruction process, the inversion scheme is slightly modified when compared to the situation for which Γ is known [3]: for each source, a pair of forward and adjoint equations is still to be solved, with a source term that differs when the source is related to the reference measurement. The computation complexity is thus not increased. As the method handles normalized quantities, it is potentially less sensitive to noise. Uncoupled reconstructions of the three physical parameters accessible by PAT obtained with this approach in experimental situations will be presented. The influence of introducing spatial prior knowledge as well as other regularization schemes will also be studied.

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