Integrated diffuse optical tomography and photoacoustic tomography: phantom validations

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Abstract: We designed, fabricated and tested a novel imaging system that fuses diffuse optical tomography (DOT) and photoacoustic tomography (PAT) in a single platform. This platform takes advantages of both DOT and PAT, and can potentially provide dual-modality two dimensional functional and cellular images of the breast quantitatively. Here we describe this integrated platform along with initial tissue phantom validations.

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OCIS codes: (110.6960) Tomography; (170.5120) Photoacoustic imaging; (170.0110) Imaging systems.

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Introduction

Photoacoustic tomography (PAT) is a potentially powerful imaging technique for visualizing the internal structure of tissue with excellent spatial resolution and high optical contrast [1–7]. While absorption coefficient images of heterogeneous media can now be recovered by quantitative PAT [8,9], it still remains a major challenge to obtain scattering coefficient from photoacoustic measurements [10].

Diffuse optical tomography (DOT), on the other hand, is another rapidly growing modality due to its high contrast in both tissue absorption and scattering, and tissue functional information available from multispectral DOT [11–15]. However, the spatial resolution of DOT is relatively low, and the detection of small targets is often impossible or distorted significantly.

In this paper, we report a novel integrated PAT/DOT system that combines the advantages of both PAT and DOT. In our hybrid modality, high resolution absorption and its derived functional images are generated through PAT, while scattering images are produced by DOT. We designed and fabricated 32 PVDF transducers, and attached them to the source/detector fiber optic array of a multispectral DOT system [11]. Diffused light and ultrasound signals are collected by DOT and PAT systems, respectively. Phantom experiments are used to validate the performance of the integrated system. Quantitative absorption and scattering images are obtained using our finite element (FE) based DOT and PAT reconstruction algorithms.

System Description

Our DOT system was previously described in detail in Ref 11. For DOT data acquisition (Fig. 1(a), left), light from a diode laser at 775nm was transmitted sequentially to 16 source points at the phantom surface through an optical switch, and diffusing light was detected by 16 photodiodes. A set of 16 × 16 measured data was then input into the DOT reconstruction algorithm to generate 2D cross-sectional images of the absorption and scattering coefficients of the phantom.
In our PAT system (Fig. 1(a), right), an Nd:YAG laser generated a pulsed 532nm beam with a pulse repetition rate of 10Hz and a pulse width of <10ns, which was delivered to the top surface of the phantom via a reflection mirror and combined concave mirror/ground glass for beam extension (The incident optical fluence was controlled below 20mJ/cm² which is the safety limit). 32 homemade transducers were used to detect the acoustic signals at 32 positions along a circular path around the phantom (Figs. 1(b) and 1(c)). Each transducer was fabricated in-house using a 110μm-thick Ag ink printed PVDF film as the sensing unit (5 × 30mm) and backing materials. A 3mm diameter hole (Fig. 1(b)) was drilled/eroded in the center of backing materials and the corresponding area of Ag ink on PVDF film for the transmission/receiving of DOT signals. The frequency response of each PVDF transducer had a bandwidth of up to 2MHz. These 32 transducers were grouped to 4 with each containing 8 transducers for signal acquisition. The complex acoustic wavefield signals were amplified by a multi-channel preamplifier and further amplified by an amplifier with a controllable gain from 30dB to 40dB. The data acquisition sampling rate was 50MHz.

Phantom Experiments

We demonstrate the ability of our integrated imaging system through several tissue-like phantom experiments with different contrasts between the target and the background. Figure 2 depicts the geometrical configuration for the test cases which consists of a circular background region (radius = 35mm) with an embedded circular target (radius = 3mm) offsetting 10mm. Three tissue-like phantom experiments were conducted. Tissue absorption and scattering were simulated with India ink and Intralipid, respectively. Agar powder (2%) was used to solidify the mixed Intralipid–India ink solution. Table 1 lists the absorption and reduced scattering coefficients of the target and background for the three phantom experiments.

| Target  | Background |
|---------|------------|
| aµs     | µ′         |
| µs      | µ′         |
| Case1   | 0.021      | 1.0        | 0.007      | 1.0        |
| Case2   | 0.014      | 2.0        | 0.007      | 1.0        |
| Case3   | 0.028      | 4.0        | 0.007      | 1.0        |

Fig. 2. Phantom geometry. R1 = 35mm, R2 = 3mm and d = 10mm.

FE based dual-meshing reconstruction algorithms described in Refs. 8,9 were used to recover quantitative absorption images from PAT data. A fine mesh of triangular elements with 6285 nodes and a coarse mesh with 1604 nodes were applied in the reconstruction, and the images were converged within 50 iterations in a parallel computer.

DOT images were reconstructed using our FE based reconstruction algorithms detailed in Refs. 13,14. In the reconstruction, a single mesh of 700 nodes and 1334 triangular elements was applied, and the images were converged within 15 iterations in a 3GHz PC with 0.99-GB memory.
Results and Discussion

Reconstructed results are shown in Figs. 3 and 4 where the pink-colored region (at 3 o’clock) clearly indicates the location and size of the object (Figs. 3(a), 3(c), 3(e), 3(g), 3(i), 3(k), 4(a) and 4(c)). As can be seen, the images formed are shown to be qualitatively correct in visual content for all the cases. To provide a more quantitative assessment of these images, the reconstructed optical property distributions are displayed along one transect through the center of reconstructed target—the one perpendicular to the line through the centers of both the target and background regions—compared with the exact values, in Figs. 3(b), 3(d), 3(f), 3(h), 3(j), 3(l), 4(b) and 4(d). Table 2 provides the quantitative information about the center and the full-width-half-maximum (FWHM) of the object as well as the recovered average optical properties of the object estimated from a region-of-interest (ROI) determined by the center and the FWHM of each object.

From the recovered absorption coefficient images, while we can see that the value of absorption coefficient is well reconstructed both from DOT and PAT data for all the cases, the location and size of target are much better recovered by PAT than that by DOT. For example, the relative errors of the recovered absorption coefficient by DOT are, 2%, 14%, and 4%, for

![Fig. 3. Reconstructed absorption coefficient images and profiles through the transect from PAT and DOT. (a) and (b): Case 1 from PAT; (c) and (d): Case 1 from DOT; (e) and (f): Case 2 from PAT; (g) and (h): Case 2 from DOT; (i) and (j): Case 3 from PAT; (k) and (l): Case 3 from DOT.](image)

![Fig. 4. Reconstructed reduced scattering coefficient images and profiles through the transect from DOT. (a) and (b): Case 2; (c) and (d): Case 3.](image)
cases 1-3, respectively, while the relative errors of the reconstructed absorption coefficient by PAT are, 16%, 1%, and 3%, for cases 1-3, respectively. For the DOT images, while the target is detected, we note that the reconstructed target position is slightly shifted relative to the exact target position. The PAT recovered target size is found to be 7.1mm, 5.3mm, and 6.1mm for the three cases, respectively, whereas the DOT recovered target size (11-14mm) is significantly overestimated compared to the exact size.

Table 2. Reconstructed Values of Absorption and Reduced Scattering Coefficients (mm$^{-1}$) of the Target and Background and Target Location (Off-Center) and Size (mm) for the Phantom Experiments*

| Test | Target | Background |
|------|--------|------------|
|      | Location | Size | Value | Location | Size | Value | Value | Value | Value |
| Case1 | Exact | 10.0 | 6.0 | 0.0210 | - | - | - | 0.0070 | - |
|      | PAT | 10.6 (6%) | 7.1 (18%) | 0.0243 (16%) | - | - | - | 0.0085 (21%) | - |
|      | DOT | 10.6 (6%) | 13.1 (118%) | 0.0206 (2%) | - | - | - | 0.0080 (14%) | - |
| Case2 | Exact | 10.0 | 6.0 | 0.0140 | 10.0 | 6.0 | 2.0 | 0.0070 | 1.0 |
|      | PAT | 10.5 (5%) | 5.3 (12%) | 0.0130 (1%) | - | - | - | 0.0073 (4%) | - |
|      | DOT | 9.2 (8%) | 14.2 (137%) | 0.0139 (1%) | 9.4 (6%) | 5.9 (2%) | 1.8 (10%) | 0.0088 (26%) | 1.1 (10%) |
| Case3 | Exact | 10.0 | 6.0 | 0.0280 | 10.0 | 6.0 | 4.0 | 0.0070 | 1.0 |
|      | PAT | 10.6 (6%) | 6.1 (2%) | 0.0271 (3%) | - | - | - | 0.0072 (3%) | - |
|      | DOT | 9.2 (8%) | 11.4 (90%) | 0.0268 (4%) | 9.6 (4%) | 6.2 (3%) | 3.8 (5%) | 0.0084 (20%) | 1.1 (10%) |

*The relative error for each recovered parameter compared to their exact value is also given in parenthesis.

From Fig. 3, we noticed that the recovered target size and absorption value are more accurate when the contrast is increased for both DOT and PAT. The PAT image showed some target distortion (Fig. 3(a)) when only absorption contrast existed. This could be due to the use of a small number of transducers and the lack of target scattering contribution to the PAT reconstruction through the optical fluence/photon density. This can be improved by adding more transducers to the PAT system.

We also noted that some artifacts appear in the DOT images especially for case 1 (Fig. 3(b)). These artifacts generally are shown near the boundary source and detector positions where the measurement sensitivity is highest. However, such boundary artifacts are not seen in the PAT absorption images.

From Fig. 4, we see that the scattering images for both cases are recovered with high quality without boundary artifacts by DOT. In addition, we found that the recovered size of the target ranges from 5.9mm to 6.2mm, in good agreement with the actual object size of 6mm. The recovered off-center location of the target ranges from 9.4mm to 9.6mm, also in good agreement with the actual off-center location of 10mm. Finally, we see that the scattering coefficient values of target and background are well recovered quantitatively as seen from Table 2.

Conclusions

In sum, we have presented a hybrid PAT and DOT system that combines the advantages of both PAT and DOT. We showed that quantitative absorption and reduced scattering coefficient images can be obtained from this system using tissue-like phantom experiments. We are currently improving this hybrid modality by adding 64 transducers to the PAT system, and will
apply it to the *in vivo* detection of breast cancer after its considerable phantom evaluation. In addition, we are implementing ideas that use the higher resolution absorption image by PAT as *a priori* knowledge for improved recovery of scattering image by DOT, or that consider the inhomogeneous scattering distribution provided by DOT to enhance the quantitative recovery of absorption coefficient by PAT, similar to the work described in Ref. 16 where we used the diffusing light measurements to assist in quantitative reconstruction of absorption coefficient by PAT. We plan to report the results from these studies in the near future.

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*Publisher's note:* Typographical errors in data in Table 2, column 3, rows 1 and 3 were corrected December 21, 2011.