Published in final edited form as:

Acad Radiol. 2014 February ; 21(2): 141–150. doi:10.1016/j.acra.2013.09.025.

Adaptable Near-Infrared Spectroscopy Fiber Array for Improved Coupling to Different Breast Sizes During Clinical MRI

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Abstract

Rationale and Objectives—Near-infrared spectroscopy (NIRS) of breast can provide functional information on the vascular and structural compartments of tissues in regions identified during simultaneous magnetic resonance imaging (MRI). NIRS can be acquired during dynamic contrast-enhanced MRI (DCE-MRI) to accomplish image-guided spectroscopy of the enhancing regions, potentially increasing the diagnostic specificity of the examination and reducing the number of biopsies performed as a result of inconclusive MRI breast imaging studies.

Materials and Methods—We combine synergistic attributes of concurrent DCE-MRI and NIRS with a new design of the clinical NIRS breast interface that couples to a standard MR breast coil and allows imaging of variable breast sizes. Spectral information from healthy volunteers and cancer patients is recovered, providing molecular information in regions defined by the segmented MR image volume.

Results—The new coupling system significantly improves examination utility by allowing improved coupling of the NIR fibers to breasts of all cup sizes and lesion locations. This improvement is demonstrated over a range of breast sizes (cup size A through D) and normal tissue heterogeneity using a group of eight healthy volunteers and two cancer patients. Lesions located in the axillary region and medial-posterior breast are now accessible to NIRS optodes. Reconstructed images were found to have biologically plausible hemoglobin content, oxygen saturation, and water and lipid fractions.

Conclusions—In summary, a new NIRS/MRI breast interface was developed to accommodate the variation in breast sizes and lesion locations that can be expected in clinical practice. DCE-MRI-guided NIRS quantifies total hemoglobin, oxygenation, and scattering in MR-enhancing regions, increasing the diagnostic information acquired from MR examinations.

Keywords

Biomedical optics; magnetic resonance imaging; spectroscopy; tomography

Breast cancer is a complex biological disease that presents challenges for detection and diagnosis. Mammography, the current gold standard for breast screening, has an overall sensitivity and specificity reported to be 77% and 97%, respectively, in a randomized multicenter trial (1). However, the technique is much less effective in women with mammographically dense breasts, in which the sensitivity and specificity fall considerably to 63% and 89%, respectively (2). Women with more dense breasts have both higher incidence of and mortality from breast cancer. They are also the most difficult group to screen with mammography (3–5). Therefore, current clinical care includes breast dynamic contrast-enhanced magnetic resonance imaging (DCE-MRI) for screening of high-risk patients (6,7). DCE-MRI is recommended for screening this population in combination with mammography because it has greater sensitivity than standard mammography, reported to be 93%–100% (8,9). Screening specificity with DCE-MRI is less consistent. It generally causes 3- to 5-fold more false-positive findings than mammography, leading to more unnecessary biopsies and invasive procedures that are stressful for patients. In this study, the coupling of near-infrared spectroscopy (NIRS) with breast MRI is examined with a new interface that allows substantially improved flexibility in delivering the combined examination to the breast than previous versions.

Combined NIRS and MRI is an emerging imaging approach that could benefit patients after screening (10) by increasing the specificity of DCE-MRI before biopsy (11). The technique can be used to noninvasively quantify oxy- and deoxy-hemoglobin, water and lipid content, and scattering parameters in adipose and fibroglandular tissues. Combined NIRS and MRI systems have been developed in the United States and Germany for human imaging (12,13), but they have been slow to progress because of design challenges and cost. However, incentives exist to develop MRI/NIRS based on promising results from stand-alone NIRS. Hundreds of patients have undergone stand-alone NIRS breast imaging at multiple academic centers in the United States and Europe (14,15). In addition, several commercial systems have been developed (16,17). The sensitivity and specificity of breast cancer detection with NIRS alone varies depending on the system geometry but has been reported to be in the range of 91%–96% and 93%–95%, respectively (18,19). Because MRI information can be used to guide image reconstruction in MRI/NIRS, the technique may improve on the stand-alone NIRS results, especially when lesions are smaller than 1–2 cm. The spatial correlation between the data streams of MRI and NIRS has the potential to provide complementary information (13,20).

The greatest challenge that the technology faces is the ability to deliver light to the subject's breast within the confines of the bore of the MR scanner when an examination is underway. The coupling interface must hold fibers in contact with the breast, while also being able to accommodate multiple breast sizes and compositions. The task has been accomplished by coupling optical fibers and/or optical detectors into custom MR breast coils in various configurations (12,21–23). NIRS has typically been integrated into custom MRI breast coils that use a parallel plate design. For example, Ntziachristos et al. produced the first MRI-guided NIRS system, which used a source fiber grid of 8×3 and a detector fiber grid of 4×2 arranged in a parallel plate geometry. Carpenter et al. also used a parallel plate configuration but with 16 fiber optics placed in two rows, adjustable by height in three positions. More recently, Mastanduno et al. developed a parallel plate array capable of being

remotely repositioned to any height. Although the parallel plate design is the clinical standard for MR-guided breast biopsy, it is not the optimal arrangement for NIRS because coverage near the chest wall is difficult to provide, making examination of women with small breasts, dense breasts, or posteriorly located tumors nearly impossible. We have addressed these practical issues by realizing a NIRS-compatible breast coil that is capable of imaging more breast sizes with a more variable range of tissue heterogeneity.

The NIRS interface described here was designed to accommodate multiple breast sizes and composition, while also providing optical coverage of the entire region of interest. Another goal was to minimize geometrical distortions of the breast being scanned and preserve the shape of the contralateral breast to maintain MR image quality. The interface is based on a triangular arrangement of optical fibers with six degrees of freedom for adjustment. We demonstrate that robust fiber contact occurs with breasts of all cup sizes during simultaneous MR and NIRS breast examinations involving healthy volunteers and cancer patients, using a typical V-shaped clinical breast coil. Results are compared to the previous generation of breast interface design.

MATERIALS AND METHODS

Human Subject Imaging

Our imaging protocol for human subject examination was approved by the Committee for the Protection of Human Subjects at Dartmouth-Hitchcock Medical Center and at Xijing Hospital. Written consent was obtained during which the nature of the procedure was fully explained to each volunteer. Subjects were positioned into the triangular breast interface while prone on the MR examination table by bringing the fiber optic cables into contact with the breast. In cases of smaller breast sizes, all fibers were not in contact with the skin surface because of curvature, and data from these channels were not used during image reconstruction. The interface involves mild compression as is the standard in MR biopsy plates to maintain patient comfort during the imaging procedure. Coregistration between optical and MR images was accomplished through MR fiducial markers placed in the plane of each set of fibers, and MR images were acquired with the slice direction in the axial geometry. NIRS and MR data were collected concurrently with data acquisition requiring 15 and 30 minutes, respectively. Because the data collection from the two imaging modalities do not interfere with each other, optical data were typically collected twice per subject as time permitted.

Instrumentation

The MRI/NIRS system deployed in this study (24) consists of six intensity modulated laser diodes and three continuous-wave laser diodes with wavelengths spanning from 660 to 850 nm, and 900 to 950 nm, respectively. Sixteen sequential source positions illuminate the breast through a custom optical switch. During each individual source illumination, the remaining 15 fibers detect transmitted light with photomultiplier tubes (Hamamatsu, Middlesex, NJ, USA, 9305-03) and large active area photodiodes (Hamamatsu, Middlesex, NJ, USA, C10439-03). The amplitude and phase (when available) of the detected light are separated by lock-in detection. The NIRS imaging system is located in the MR console

room, and 12 m fiber bundles with 4 mm working optical diameters are passed through a custom penetration panel to enter the MR scanner room. These fibers are coupled into a clinical breast coil for simultaneous MR and NIRS imaging of patients or phantoms. Clinical MRI image quality and acquisition time are not affected by the addition of the NIRS fiber array. An overview of the NIRS system is presented in Figure 1. More details on the imaging instrumentation can be found in a previous publication (24).

Recent work on the development of this system has focused on the fiber interface's ability to accommodate variable breast sizes and compositions through a clinical MRI breast coil (Invivo Corp, Gainesville, FL) retrofitted with the optical fiber array. An adjustable triangular breast interface was designed using Solidworks (Solidworks Corp, Waltham, MA) and fabricated using a three-dimensional printer (Stratasys, Inc., Eden Prairie, MN), which deposits acrylonitrile butadiene styrene plastic and white acetal, both MR-compatible materials. The design is unique to optical tomography and provides patient-specific adjustments without the need for a custom MR breast coil. The interface, shown in Figure 2, is based on 16 fiber optic bundles divided into one set of eight and two sets of four fibers. The set of eight fibers, located on the lateral side of the breast, incorporates a slight curvature (radius, 8 in) to couple to smaller breasts more effectively. These fibers not only slide in the mediolateral direction, similarly to a breast biopsy plate, but also in the anteroposterior direction to adjust for different breast diameters.

The interface consists of two additional sets of four fibers on the medial side of the breast, one of which is offset slightly superiorly, whereas the other is positioned slightly inferiorly. Both sets of fibers are angled toward the center of the breast. They can be adjusted for different breast diameters. At the maximum extent of their range, the medial sets of fibers extend beyond the surface of the breast coil to cover tissue nearest the chest wall.

These fibers are secured using nylon set screws and translate across friction-coupled dovetailed tracks. They slide easily for adjustment. After being positioned against the subject's breast, a lock is inserted to prevent further movement. The lock ensures that the fibers remain stationary and are mildly compressed against the breast surface during imaging. Breast stabilization is also important to minimize MR image artifact. Because the technique is an adjunct to clinical breast MRI, we were also careful not to interfere with the imaging of the contralateral breast.

Optical Image Reconstruction

Breast images are processed and reconstructed with the open source software platform, NIRFAST (25). Briefly, the difference between measured data and a diffusion-based model of light propagation through the medium (26–28) is minimized to yield estimates of the optical properties of the tissue of interest. The lossy diffusion equation has been well studied in this setting and is an acceptable approximation in tissues where scattering (μ_s') dominates absorption (μ_a) and source–detector separation is greater than one scattering distance (29,30). Model data are calculated using the frequency domain diffusion equation (Eq. 1),

$$-\nabla \cdot \mathbf{D} \nabla \Phi(\mathbf{r}, \omega) + \left(\mu_a = \frac{i\omega}{c} \right) \Phi(\mathbf{r}, \omega) = \mathbf{S}(\mathbf{r}, \omega), \quad (1)$$

discretized on finite elements. Here, a source, S , with frequency, ω , describes light fluence, Φ , through the turbid media. We also use a modified Tikhonov regularization routine with regularization parameter, λ , using a Levenberg–Marquardt iterative update, which stabilizes the estimation process by reducing the effects of noise on the image reconstruction, and eliminating improbable solutions (31). The image formation algorithm (Eq. 2) is nonlinear and solved with a Newton-type minimization method for c within the matrix equation (32):

$$\left(J^T J + \lambda I \right) \Delta c = J^T \Delta \delta, \quad (2)$$

that optimizes the estimation of the physiological parameters, c , which include oxygenated and deoxygenated hemoglobin concentrations, water fraction, scatter amplitude, and scatter power (23,24). We typically report total hemoglobin, $HbT = HbO + Hb$, and oxygen saturation, $StO_2 = \frac{HbO}{HbT}$, from these parameters. Here, J is the Jacobian matrix, I is the identity matrix, and δ is the model-data misfit. Selection of λ influences the resulting solutions (33), and it is chosen based on inherent system noise and fiber coupling errors, which are difficult to quantify in general because they can be case specific (34).

The three-dimensional reconstruction algorithm was designed to use a priori information gained from MRI to guide the optical solution as outlined in previous work by Carpenter et al. (22). This technique makes the assumption that each of the segmented regions defined from the MR, adipose and fibroglandular, have similar optical properties throughout. We simplify the image reconstruction problem computationally by completely eliminating variation within regions and thus, are able to quantify optical properties between regions but not within them (35). An axial slice from the optical reconstruction volume is then overlaid on the same axial MRI slice for interpretation. The optical solution for the adipose region is censored to enhance the visualization of the recovered parameters in the glandular region and any contrast-enhancing MRI regions of interest.

RESULTS

Triangular Interface Performance

Basic functionality of our triangular breast interface was evaluated by imaging tissue-simulating phantoms and recovering the associated images using MR prior information (23,36,37). We then tested the interface for functionality on a healthy volunteer with an A-cup breast size by positioning optodes in contact with the tissue and scanning her with MRI/NIRS. In this case, we successfully positioned 15 of 16 optodes in contact with the breast within 1 cm from the chest wall as shown in Figure 2. One fiber was not in contact with tissue because of the curvature of the breast. Our interface covered the medial chest wall and upper outer quadrant fully. In previous designs (22–24), positioning the fibers in contact with an A-cup breast was not possible because of the thickness of the breast coil and padding.

For direct comparison, we imaged a volunteer with a B-cup-sized breast using both our previous parallel-plate optical-array geometry placed in a custom MR breast coil and the new triangular geometry integrated with a standard clinical MR breast coil. Side views of the two geometries are shown in Figure 3. In this subject, the fibers must be raised to be closer to the chest wall than is possible in the parallel plate geometry. The top side of the coil prevented the fibers from reaching closer than 1.5 cm from the chest wall before padding was added for patient comfort, leaving contact with this volunteer's breast in only two of 16 fibers, which was inadequate for imaging. In the triangular geometry, the fibers are angled and they are uninhibited by the top of the coil platform and find contact with the chest wall directly. The triangular interface was able to easily contact the same breast with 15 of 16 fibers, and produce a successful NIRS image. The V shape of the clinical coil also provided better access to the upper outer quadrant of the breast.

Human Subject Imaging

The triangular breast interface was used to examine eight healthy volunteers with variable breast cup sizes and two pre-surgical cancer patients. A bilateral axial MR image from each subject is presented in Figure 4. Our new triangular interface was able to recover optical images successfully from each volunteer despite the widely varying breast size, shape, density, and composition. Breast density was characterized based on MRI images by a radiologist experienced in breast MRI and mammography. We performed imaging procedures on three A-, two B-, two C-, and one D-cup breast sizes. In the smaller and more difficult to access breasts (A- and B-cups), the interface was typically extended as high as it can traverse and in as small of a diameter as it can maintain. When imaging the larger breast cup sizes (C and D), we also tried to center the fibers on the breast coronally because the curvature is larger and easier to accommodate.

Figure 5 shows a combined image set from both of our C-cup volunteers, one of dense composition and the other of fatty composition. In both cases, we were able to contact the breast with all 16 fibers. We display images overlaid on the corresponding axial MRI slice and color coded specific to the NIRS chromophore being represented. In each case, the adipose region is transparent, but the color bar approximately represents its value.

Finally, we grouped our volunteer subjects by MR breast density. Figure 6 shows data when subjects were grouped as either dense or not dense, as defined by a radiologist experienced in breast MRI. In both groups, total hemoglobin was higher in the glandular region compared to adipose with the difference being statistically significant ($P = .0412$) in the dense group. No noticeable trends in oxygen saturation were found between tissue types or between groups, each being near 80% oxygenated. The water content was higher in the glandular regions in both groups and higher in the dense group relative to the not-dense group, but not to a statistically significant level. The lipid content of adipose tissue was higher than glandular tissue in both groups. The dense group had lower lipid content in the adipose tissue than the not-dense group with statistical significance ($P = .015$). These results are promising as the fiber interface enabled the acquisition of NIRS images consistently across all breast sizes with physiologically reasonable responses.

This device was also tested in presurgical cancer patients. Figure 7 shows a malignant case with a centrally located lesion (size, $20 \times 17 \times 15$ mm) in a D-cup-sized breast. The lesion displayed wash in/wash out contrast enhancement kinetics and was bright on T2-MRI. We were able to position the fiber optics near the lesion and found that it had total hemoglobin concentration of 1.42 times the surrounding tissue. Oxygen saturation, water content, and scattering parameters were observed to be lower in the tumor. A benign case involving a B-cup-sized breast and an anterior lesion (size, $6 \times 5 \times 5$ mm) is shown in Figure 8. This abnormality presented mild continuous enhancement. We were able to target the small lesion effectively with the triangular breast interface and found that the total hemoglobin content was 0.74 times the surrounding tissue. All the other NIRS parameters were slightly lower as well. Results from the patients with abnormal optical images are summarized in Table 1. As with the healthy volunteers, the triangular fiber interface was able to accommodate these breast sizes and lesion locations, and the MR-compatible NIRS system obtained results suggestive of abnormality status, which is promising for future evaluative studies of the combined imaging approach.

DISCUSSION

Triangular Interface Development

The ideal MRI/NIRS breast interface must adapt to patient size, be easily adjustable, and provide adequate volumetric sampling. It must maintain fiber contact with tissue during the breast examination, be repeatable from one examination to the next, and be comfortable for the subject. MR image quality of the contralateral breast should also be unaltered because MRI has a high sensitivity to lesions in that breast (38). Finally, the interface should be adaptable to a range of clinical breast coils rather than be integrated into a single manufacturer's design coil. Although our unit is imperfect, we have addressed all these issues and found that the most significant improvement is its ability to image variable breast sizes, provided they are compatible with a standard clinical breast coil platform.

In moving away from the traditional parallel plate geometry, we have improved considerably the prescan adjustability but at the expense of interactively selecting the slice during the imaging examination (23). As fibers are now arranged in a triangle rather than parallel plates, considerably less compression is required to achieve fiber contact with the breast tissue. Additionally, the triangular design separates the fibers from the contralateral breast, minimizing any effects on the MR image quality.

One advantage of the parallel plate design is the relative simplicity of the finite element mesh required for NIRS image reconstruction. Rather than a smooth-sided rectangular shape, breasts imaged in the triangular geometry tend to be more irregular with indentations occurring where fibers contact the skin, which makes mesh generation more time consuming and technically demanding, although algorithms and computational resources are improving. This concern increases with patient volume because meshes must be customized for every subject. Seemingly, the fiber indentations could be eliminated without compromising functionality, mitigating the drawback in the future, if it proves important.

Smaller breast sizes present the additional challenge to previous MRI/NIRS breast coil designs that they are also likely to be more dense. Density increases breast cancer risk, and this subgroup of women must not be ignored (39). The parallel plate interfaces used in previous studies were able to position fibers within 1.5 to 2 cm of the chest wall (10,22), which is not sufficient for NIRS imaging of smaller cup sizes (A and B) and very dense breasts. An example is shown in Figure 3, in which fiber coupling in the parallel plate geometry prevented NIRS imaging of a B-cup-sized breast. The triangular interface was able to accommodate this volunteer and many others who were not able to undergo a successful NIRS examination in the past, which represents a significant step forward in the clinical acceptance of the technology.

Although the present design for MRI/NIRS is an improvement, it is not perfect. Foreexample, the fiber translation friction couplings, which can be difficult to use and often require some adjustments to be made from the medial side, whereas, ideally, all adjustments would be made from the lateral side of the patient, where technologist access is much simpler and less intrusive. The access question is challenging given the space constraints within standard breast coil systems, but state-of-the-art breast biopsy coils have already incorporated these types of adjustments, and future designs would likely benefit from a triangular array that is coupled directly to the biopsy plates.

Human Image Interpretation

Because the primary benefit of our design was to accommodate variable breast sizes, we tested our approach on women with breasts representing some of the natural heterogeneity, shape, and size that would be expected in clinical practice. Specifically, we successfully examined eight healthy volunteers with cup sizes of A through D and fatty and dense parenchymal compositions. All subjects were quickly positioned (less than 5 minutes) and did not report discomfort due to the procedure. The triangular interface performed extremely well in the small cup sizes, allowing us to image both A- and B-cup breasts for the first time with almost all fibers in contact because we were able to position fibers very close to the chest wall. In larger breasts, our interface performed equally well. We were able to target the entire breast, which is important for localizing suspicious regions in the diagnostic workup of a typical MRI patient. The patients we successfully imaged with abnormalities had lesions in central and anterior locations within the breast. Finally, the interface provided unprecedented access to the axillary region and upper outer quadrant of all breast sizes, which is a common lesion location (40). Based on our experience in examining this group of healthy volunteers, we predict that the triangular interface will provide complete coverage and accurate targeting of lesions in all breast sizes.

When compared to results from studies of other healthy volunteers in both MR- and non-MR-guided NIRS systems, we find that our chromophore quantification is physiologically reasonable and comparable (22,28,41,42). In our cohort of eight subjects, oxygen saturation fell between 75% and 95% for all tissue types and categories. Our system also estimated average water, lipid, and hemoglobin concentrations to within normal physiological limits for each tissue type, illustrating the capability of the MRI/NIRS breast coil. We saw an increased hemoglobin concentration in the malignant case and a decreased concentration in

the benign case. In previous works (43,44), relative hemoglobin concentration has been shown to be an indicator of tissue malignancy, and we are optimistic about future patient studies using the new breast-imaging interface.

The absolute values of our tissue components occur within physiological limits, but were not as robust as the relative quantification, as is commonly reported for other imaging modalities (45). The variation in our images could stem from factors other than the natural variation between subjects. For example, our current system provides fairly low spectral resolution with only nine wavelengths, making it susceptible to noise in the data from instrumentation or variations in fiber coupling that creates cross talk between chromophore estimates (34). Furthermore, with only six wavelengths of frequency domain data, codependencies in the absorption and scattering information are probable (45). Finally, effects from partial volume averaging are likely to occur in these healthy volunteers because even with anatomical priors, pure separation of absorption and scattering is difficult because of the blended sensitivity profiles across tissue types. As a result, we may see water and lipid content distorted in the adipose region relative to its glandular counterpart (46). In future studies, the presence of a locally defined target could help to alleviate the effect. Thus, we are confident in our ability to recover optical properties of smaller areas of interest based on previous phantom results (36,47).

One of the major challenges in combining NIRS with MRI has been source–detector coupling to the breast within the confines of the MR bore, which influences the breast sizes and densities that can be imaged and partially determines whether NIRS is a useful addition to MRI. In this work, the design and evaluation of a triangular optical fiber interface integrated with a standard clinical MRI breast coil was shown to improve patient positioning and imaging in MRI/NIRS, especially in terms of simultaneous MRI and NIRS imaging of breast cup sizes A and B as well as C and D. We demonstrated fiber coupling over all breast cup sizes, normal parenchymal heterogeneity found in a group of eight healthy volunteers, and abnormal tissue found in two patients with breast abnormalities. Data collected from these examinations were reconstructed to quantify chromophore concentration in adipose, fibroglandular, and suspicious tissues with physiologically reasonable values. Future work with this system will focus on the imaging of patients with lesions in many locations to evaluate the potential for MRI/NIRS to add to the sensitivity and specificity of DCE-MRI.

Acknowledgments

This work was funded by National Institutes of Health grant R01 CA069544 and National Natural Science Foundation of China 81101091.

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Figure 1.

Frequency domain near-infrared spectroscopy (NIRS) system (a) couples to clinical 3T–magnetic resonance imaging (MRI) (b) through NIRS/MRI breast coil (c). Bilateral MRI images (d) are acquired with nominal interference. *Green arrows* highlight location of NIRS optodes. Images are reconstructed for total hemoglobin (HbT) (e), blood oxygenation (f), water (g) and lipid fraction (h), scatter amplitude (sa) (i), and scatter power (sp) (j). StO₂, oxygen saturation. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Figure 2.

Side view of near-infrared spectroscopy/magnetic resonance imaging (MRI) breast coil with *green arrows* representing available degrees of freedom (a). The optodes can accommodate both large (b) and small (c) breast diameters. Axial (d) and coronal (e) MRI images of an A-cup-sized breast show fiber locations corresponding to surface projections of the medial (f) and lateral (g) sides. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Figure 3.

Comparison of previous design of near-infrared spectroscopy/magnetic resonance imaging breast coil. Side view of parallel plate interface (**a**) and coronal image of a B-cup–sized volunteer (**b**). *Green arrows* show where fibers are located. A surface projection (**c**) illustrates acceptable (*green*) and poor (*red*) fiber contact. Side view of triangular breast interface (**d**) and axial image of the same volunteer (**e**). *Green arrows* show where fibers are located. A surface projection (**f**) illustrates significant improvement in fiber contact. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Figure 4. Bilateral axial images of all healthy volunteers imaged in this study arranged by cup size. The near-infrared spectroscopy/magnetic resonance imaging breast coil was able to accommodate all sizes, densities, and compositions in the group.

Figure 5.

Images from two C-cup-sized volunteers of total hemoglobin (HbT), blood oxygenation, water and lipid fraction, scatter amplitude (sa), and scatter power (sp) along with their current craniocaudal (CC) and mediolateral oblique (MLO) mammograms. StO₂, oxygen saturation.

Figure 6.

Data from all subjects grouped by magnetic resonance breast density (four subjects per group). Glandular tissue shows higher hemoglobin levels than adipose tissue, whereas not-dense breasts show higher lipid levels than dense breasts with statistical significance ($*P < .05$). HbT, total hemoglobin; StO₂, oxygen saturation.

Figure 7.

Images from a patient with a malignant lesion ($20 \times 17 \times 15$ mm) seen on T2-magnetic resonance imaging. The patient had a D-cup-sized breast with fatty composition. We were able to position all 16 optodes near the lesion (*red arrow*). This tumor showed hemoglobin levels of $1.42\times$ the background and decreases in other chromophores. In each image, the adipose region is removed for visualization purposes. HbT, total hemoglobin; sa, scatter amplitude; sp, scatter power; StO₂, oxygen saturation. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Figure 8.

Images from a patient with a benign lesion ($6 \times 5 \times 5$ mm). This patient had a B-cup-sized breast with scattered composition. We were able to achieve contact with 14/16 fibers and target the lesion (*red arrow*) effectively. The lesion displayed hemoglobin levels of $0.74\times$ the background with a slight increase in oxygen saturation. Other chromophores decreased in the lesion. In each image, the adipose region is removed for visualization purposes. HbT, total hemoglobin; sa, scatter amplitude; sp, scatter power; StO₂, oxygen saturation. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

TABLE 1

Recovered Values from Optical Imaging of Abnormal Breast Tissue in Two Patients

Tissue	Total Hemoglobin (μ M)	Oxygen Saturation (%)	Water Content (%)	Lipid Content (%)	Scatter Amplitude	Scatter Power
Patient 1						
Adipose	8.7	46.1	33.4	n/a	0.76	0.3
Glandular	12.6	60.2	44.5	n/a	1.2	0.3
Tumor	17.9	44.5	61.4	n/a	1.1	0.3
Tumor/Glandular	1.4×	0.7×	0.8×	n/a	0.9×	1.0×
Patient 2						
Adipose	12.0	64.6	27.7	72.3	1.2	0.1
Glandular	17.8	54.1	68.6	31.4	1.1	0.1
Tumor	12.7	68.4	31.2	68.8	0.85	0.1
Tumor/Glandular	0.7×	1.26×	0.5×	2.2×	0.8×	1.0×

Patient 1 was a malignant case, and the region of interest (ROI)-total hemoglobin (HbT) was 1.4 times the glandular HbT. Patient 2 was a benign case with ROI-HbT of 0.7× the glandular HbT (contrasts in bold type).