Light Guided Lumpectomy: Is Continuous Wave or Frequency Domain More Accurate

A. L. Dayton, N. Choudhury and S. A. Prahl

BME Department, Oregon Health & Science University, United States

ABSTRACT

Improving the success of lumpectomies would reduce the number of procedures, cost, and morbidity. A light source could be placed in a lesion to assist in finding and removing the lesion. A quantitive measurement of the distance between such a light source and a detector would further aid in the procedure by providing surgeons with easy to use intra-operative guidance to the lesion.

Two methods, continuous wave and frequency domain, of accomplishing this measurement were compared. Within one radio frequency experimental system, the amplitude at 15 MHz was taken to represent the continuous wave signal and the phase at 100 MHz was taken to represent the frequency domain signal. For the continuous wave method, data at source-detector separation distances of 20, 30 & 50 mm were used to predict other distances of 10, 20, 30, 40, & 50 mm. Data at source-detector separation distances of 20 & 40 mm was used to predict distances for the frequency domain method.

When the difference between the predicted distance and the actual distance was compared to zero the continuous wave method was significantly different (student's *t*-test, $p = 0.03$) while the frequency domain method was not statistically different from zero (student's*t*-test, $p > 0.05$). The frequency domain method was more accurate at predicting the source-detector separation distance between 10 & 50 mm. This frequency domain method of measuring distance may be useful in locating and removing lesions during lumpectomy procedures.

Keywords: breast cancer, frequency domain, distance, Light Guided Lumpectomy

1. INTRODUCTION

Breast conserving surgery, or lumpectomy, is frequently used for surgical control of small breast lesions. However, the success of the surgery depends on the margin status. It has been shown that positive margins occur in 10–90 % [1–7] of cases. Improving the success of lumpectomies would reduce the number of procedures for patients, cost, and morbidity. A light source placed in the lesion to be removed may be used to assist in finding and removing the lesion. Furthermore, a measurement of the distance between the light source and an optical probe is feasible.[8] Ideally, a simple intensity measurement could be made to determine such a distance because of its low cost. However, measuring distances less than 20 mm may be problematic due to low absorption in breast tissue and the limitations of the diffusion approximation to the radiative transport equation. A comparison of measurement techniques, continuous wave and frequency domain, was explored in this paper.

2. MATERIALS & METHODS

2.1 Experimental System

To compare the continuous wave and frequency domain techniques, a system was assembled as shown in Figure 1. A computer running LabView (National Instruments, v. 2009) was used to control a network analyzer (Hewlett Packard, 8752C) which generated a radio frequency (RF) signal at the desired frequency. The RF signal was delivered to a laser diode mount (ThorLabs,TCLDM9) on which an 638 nm laser diode (Sanyo, DL6148-030) was mounted. The laser diode was biased by a direct current from the driver (ThorLabs, LDC 210) of 68 mA and the

---

Further author information: (Send correspondence to S.A.P.)
S.A.P.: E-mail: prahl@bme.ogi.edu, Telephone: (503) 216-2197, 9205 SW Barnes Rd., Portland, OR 97225, USA

temperature of the diode was held at 25°C by a temperature controller (Thor Labs, TED 200C). The sinusoidally modulated light was delivered to a phantom through a 200 μm diameter optical fiber that was bundled to overfill the modes. Light was detected with a 1000 μm diameter optical fiber, also overfilled. The detected signal was focused onto an avalanche photodiode, APD, (ThorLabs, APD 210) where it was converted to voltage and fed back into the network analyzer. 101 measurements at each frequency were collected. The phase and amplitude of the detected signal were recorded with LabView.

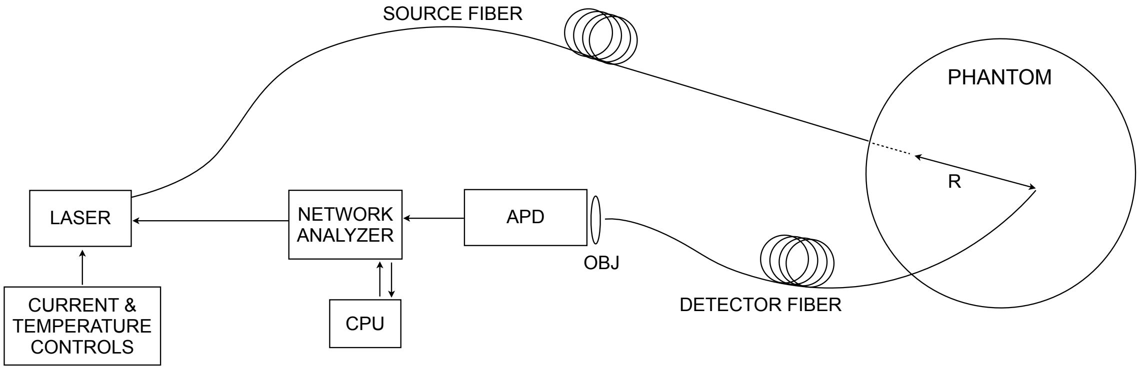

Figure 1: Experimental system indicating location of source fiber and detector fiber where R indicates the distance between source and detector.

In order to compare the two techniques, one system was used to modulate the light source. The amplitude of the signal at 15 MHz was taken to represent the continuous wave (CW) signal as there is no frequency dependent response of the amplitude at this low frequency. Any decrease in the amplitude at 15 MHz can be attributed to a reduction in the overall intensity due to scattering and absorption. The phase of the signal at 100 MHz was taken to represent the frequency domain (FD) signal.

The source fiber was centered in a 10×10 cm (diameter × height) cylinder and the detector fiber was stereotactically positioned at known distances from the source. The phantom was sufficiently large that an infinite medium was assumed. Data sets were acquired at source-detector separation distances of 10, 20, 30, 40, & 50 mm. The detector was moved to a known distance, data was acquired at each frequency and the detector was moved again.

2.2 Analysis

For the continuous wave signal, the amplitude, A, at 15 MHz at R=20, 30 & 50 mm was used with Equation 1 to solve for the optical properties of the medium and $A_\circ$, the theoretical amplitude at the source, using nonlinear optimization in Matlab (Mathworks, v 7.4).

$$A = A_\circ \frac{e^{-R/\delta}}{4\pi\mu_a\delta^2 R} \tag{1}$$

Where $\delta = \sqrt{D/\mu_a}$, $D = 1/3(\mu_a + \mu_s')$, μ_a is the absorption coefficient, μ_s' is the reduced scattering coefficient and equals $\mu_s(1-g)$ where g is the anisotropy and μ_s is the scattering coefficient. The amplitude measurements at all distances, R, and the derived optical properties of the medium, were used to predict the distance the light had traveled between the source and detector using nonlinear optimization in Matlab.

For the frequency domain signal, the phase, θ, at 100 MHz at R= 20 & 40 mm was used with Equation 2 to determine the calibration factor $\gamma = \frac{1}{\sqrt{\mu_a/D}}$.

$$\theta = -R \cdot \gamma \cdot \frac{\omega}{2c} \tag{2}$$

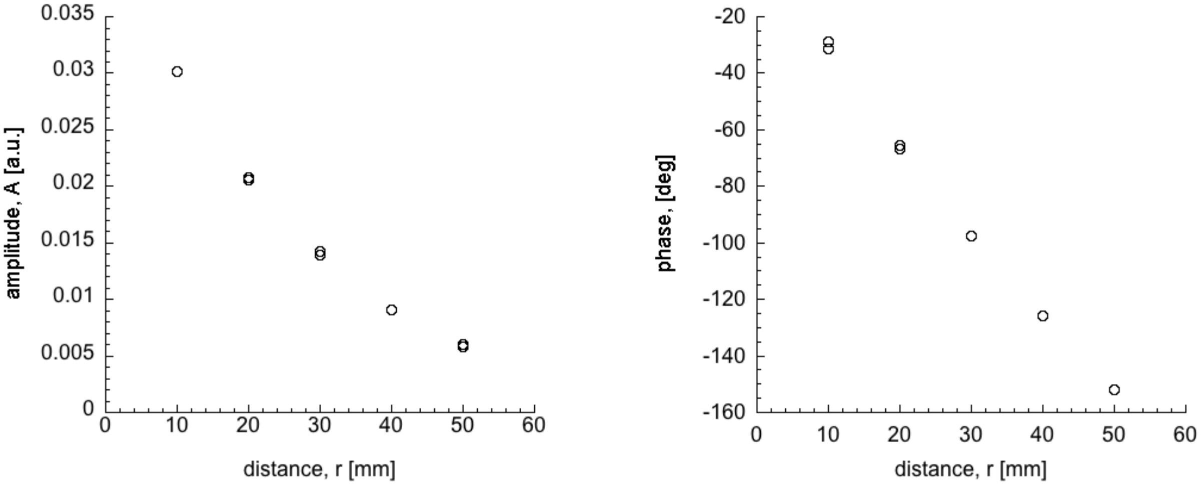

Figure 2: *Left:* Continuous wave signal: the amplitude at 15 MHz for each known source-detector separation distance, r. *Right:* Frequency domain signal: the phase at 100 MHz for each known source-detector separation distance, r.

where ω is the angular frequency of modulation and c is the speed of light in the medium. The phase measurements at all distances, R, and the derived calibration factor, γ, were used to directly predict the distance the light had traveled. Residuals were calculated for each method of predicting R by subtracting the known distance from the predicted distance.

2.3 Characterization

A 50/50 v/v mixture of skim milk and deionized water was used as a phantom. As an external validation of the optical properties of the phantom integrating sphere measurements were made. Integrating sphere measurements were made on a 3 mm thick, 60 mm diameter sample of the solution. The procedure was described in Moffitt *et. al.*[9]

3. RESULTS

3.1 Optical Properties

The absorption and reduced scattering coefficients from integrating sphere measurements were $\mu_a = 0.001\,\text{mm}^{-1}$ and $\mu_s' = 0.67\,\text{mm}^{-1}$. The continuous wave method at $R=$ 20, 30 & 50 mm resulted in $\mu_a = 0.0001\,\text{mm}^{-1}$ and $\mu_s' = 0.87\,\text{mm}^{-1}$. The discrepancy between the two techniques has not been determined.

3.2 Distance Measurements

The amplitude at 15 MHz and phase at 100 MHz is shown in Figure 2. After analysis of the data, R was predicted for each data point based either on the derivation of $A_\circ$, μ_a, μ_s' in the continuous wave analysis or γ in the frequency domain analysis. The predicted distance is plotted against the actual distance in Figure 3 as well as the residuals of each analysis. The CW residuals were significantly different from zero (student's t-test, $p = 0.03$) while the FD residuals were not statistically different from zero (student's t-test, $p > 0.05$).

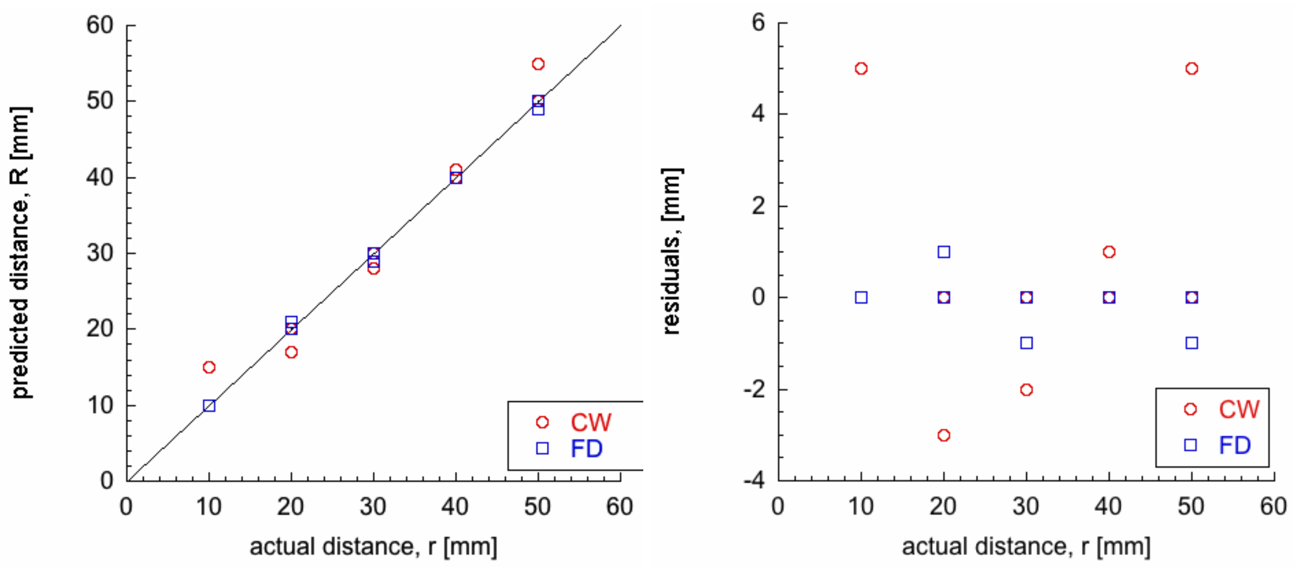

Figure 3: *Left:* Comparison of the continuous wave (CW) and frequency domain (FD) method of predicting the source-detector separation distance, R, as a function of the actual source-detector separation distance, r. The line is where the data should fall. *Right:* Residuals, the difference between the predicted distance and actual distance. The frequency domain method more accurately predicts the distance R.

4. CONCLUSION

Comparison of continuous wave and frequency domain methods of predicting the distance between a source and detector in a homogeneous medium were explored. The frequency domain method was significantly more accurate at predicting the source-detector separation distances between 10 & 50 mm. The CW method proved to be problematic. Particularly troubling was the inability of the CW data to predict distances accurately below 30 mm where high accuracy is needed. The CW method also requires one additional measurement to calibrate the system than the FD method. Although both methods implicitly rely on the diffusion approximation to the radiative transport equation the simplicity of the linear relationship between distance, R, and phase, θ may be an advantage when performing this analysis. This FD method of measuring distance may be useful in locating and removing lesions during lumpectomy procedures.

The authors would like to thank the Safeway Foundation for funding this research

REFERENCES

1. S. Renton, J. Gazet, H. Ford, C. Corbishley, and R. Sutcliffe, "The importance of the resection margin in conservative surgery for breast cancer," *European Journal of Surgical Oncology* **22**, pp. 17–22, Feb 1996.
2. H. Luu, C. Otis, W. Reed, J. Garb, and J. Frank, "The unsatisfactory margin in breast cancer surgery," *American Journal of Surgery* **178**, pp. 362–366, Nov 1999.
3. E. Obedian and B. G. Haffty, "Negative margin status improves local control in conservatively managed breast cancer patients," *The Cancer Journal from Scientific American* **6**, pp. 28–33, Jan-Feb 2000.
4. P. Tartter, J. Kaplan, I. Bleiweiss, C. Gajdos, A. Kong, S. Ahmed, and D. Zapetti, "Lumpectomy margins, reexcision, and local recurrence of breast cancer," *American Journal of Surgery* **179**, pp. 81–85, Feb 2000.
5. S. Singletary, "Surgical margins in patients with early-stage breast cancer treated with breast conservation therapy," *American Journal of Surgery* **184**, pp. 383–393, Nov 2002.
6. C. D. Scopa, P. Aroukatos, A. C. Tsamandas, and C. Aletra, "Evaluation of margin status in lumpectomy specimens and residual breast carcinoma," *Breast J* **12**, pp. 150–3, 2006.

7. C. Kotwall, M. Ranson, A. Stiles, and M. S. Hamann, “Relationship between initial margin status for invasive breast cancer and residual carcinoma after re-excision,” *American Surgeon* **73**, pp. 337–343, Apr 2007.
8. A. L. Dayton, V. T. Keranen, and S. A. Prahl, “Optical wire guided lumpectomy: frequency domain measurements,” *Optical Fibers and Sensors for Medical Diagnostics and Treatment Applications IX* **7173**(1), p. 71730M, SPIE, 2009.
9. T. Moffitt, Y. Chen, and S. Prahl, “Preparation and characterization of polyurethane optical phantoms,” *Journal of Biomedical Optics* **11**, p. 041103, July/August 2006.