Diffuse Reflectance Spectroscopy with a Self-Calibrating Fiber Optic Probe

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1. Abstract

We demonstrate a novel fiber optic probe with real-time, self-calibration capability that can be used for diffuse reflectance spectroscopy (DRS) in tissue. The probe was tested in a number of synthetic liquid phantoms in different days over a relevant range of tissue optical properties. Absorption and reduced scattering coefficients are extracted with an average absolute error and standard deviation of 6.3±2.6% and 2.2±1.4%, respectively, with an inverse scalable Monte Carlo model.

2. Motivation

- UV-Visible DRS is sensitive to the absorption and scattering of biological molecules in tissue, thus can be used as a non-invasive tool to obtain quantitative physiological and morphological information of human tissue.
- Fiber optic probes are commonly used to deliver the illumination light to and collect the diffusely reflected light from the tissue for DRS measurements.
- For DRS to be used routinely in the clinic, calibration is required to compensate for:
  - wavelength-dependent instrument and probe response.
  - lamp intensity fluctuations (>25% during warm-up, > 3% after 30 minutes, and 5-10% from day to day).
  - and fiber bending losses during measurement (up to 10%).
- Current calibration techniques [1-6] rely on measurements using power meters, reflectance standards, and/or tissue phantoms, typically after the clinical measurements are completed.
- Limitations associated with such calibration methods:
  - cannot correct for real-time lamp intensity fluctuations
  - require at least 30 minutes for lamp warm up, which is a significant problem in a clinical setting such as the O.R.
  - require an additional 10-20 minutes before or after the clinical measurement for calibration.
- It is therefore desirable to create a fast, robust and systematic calibration approach that can be used for correcting tissue optical spectra obtained at different times and with different instruments and probes.

3. Experimental Setup

- The UV-VIS DRS system consists of a broadband Xe light source, a self-calibrating (SC) fiber optic probe, a spectrograph, a CCD camera, and a laptop computer.
- The probe has a built-in calibration channel that can be used to record the lamp spectrum and instrument/fiber response concurrently with tissue measurements.
- Combined with a one time, single-reference phantom measurement, the SC probe can provide instrument-independent optical properties.

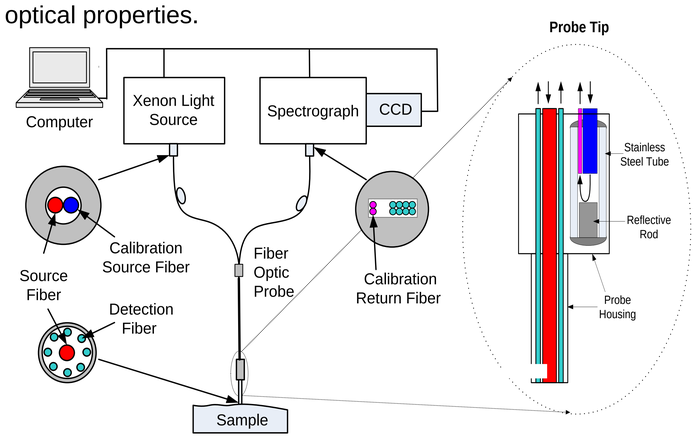


Fig.1. Schematic of the UV-VIS DRS system using a self-calibrated fiber optic probe. The detection fibers and calibration return fibers are imaged on to the 2-D CCD as two separate tracks.

4. Correction for Lamp Warm-up

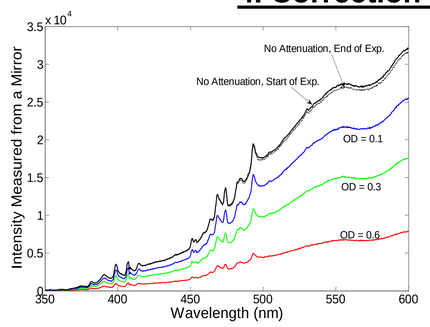


Fig.2. Raw spectra from a mirror at different levels of attenuation using an ND filter or at no attenuation.

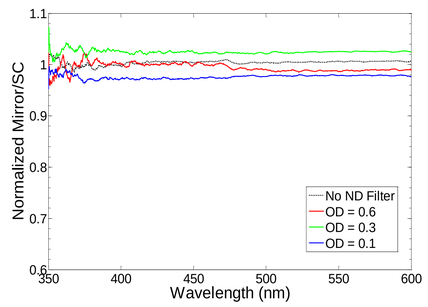
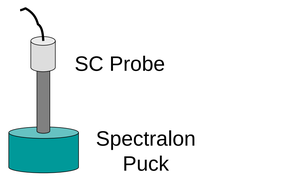


Fig.3. Ratio between mirror and self-calibration spectra normalized to the first scan (no filter).

The variation in the illumination intensity is reduced from 6 dB to less than 0.25 dB

5. Correction for Wavelength Dependence of SC Channel



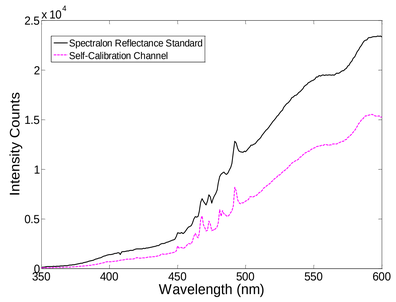


Fig.4. Raw spectrum from a diffuse reflectance standard (puck) and the calibration spectrum obtained concurrently.

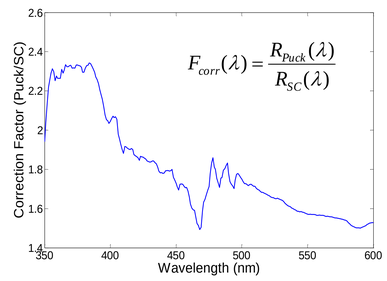


Fig.5. Correction for the wavelength response difference between the two channels.

6. Clinical Data Calibration

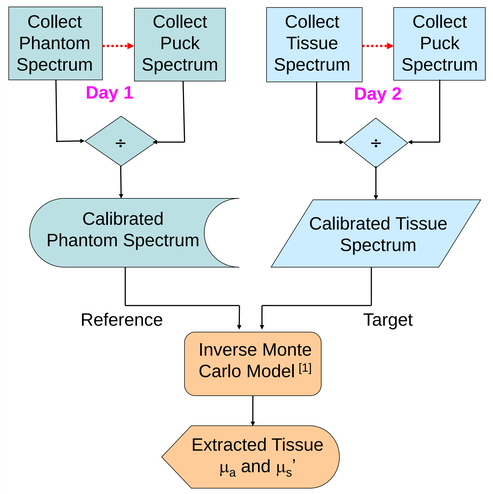


Fig.6. Calibration procedures using a puck.

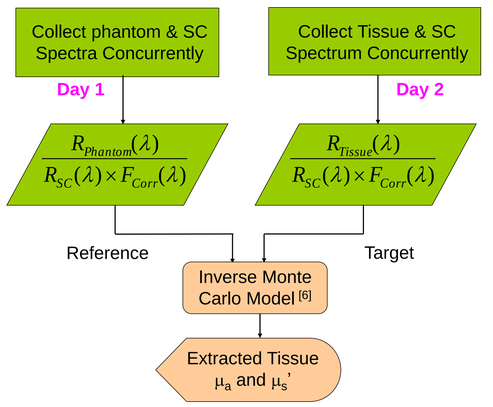
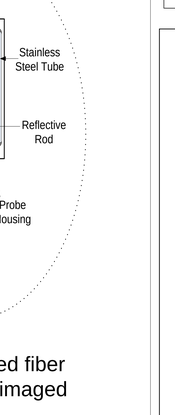


Fig.7. Self-calibration procedures.

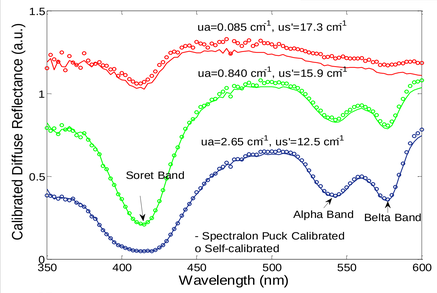


Liquid Phantom

7. Phantom Experiments

- Reflectance spectra were collected from two phantom sets of similar range of optical properties, but in different days: Days 1 & 2.
- 17 successive Hb titrations with a fixed number of absorbers in each phantom set.
- Absorber: hemoglobin, [Hb] concentration: 1 – 32 μM
- Scatterer: 1 μm polystyrene microspheres, μ_s' = 11.56 – 19.1 cm^{-1} (between 450-600 nm)
- Reference phantom #14: [Hb]=21.16 μM, wavelength averaged μ_s'=14.2 cm^{-1} (over 450-600 nm)
- A measurement was made from the puck at the end.

8. Results



$$R_{puck\_calibrated} = \frac{R_{tissue}}{R_{puck}}$$

$$R_{sc\_calibrated} = \frac{R_{tissue}}{R_{sc} \cdot F_{corr}(\lambda)}$$

Fig.8. Puck- and self-calibrated spectra for three phantoms (lightest, medium and darkest) from Day 1. μ_a and μ_s' are averaged over 450-600 nm. The differences between the spectra for phantom #1 (Red) indicates that the puck failed to correct for system drift.

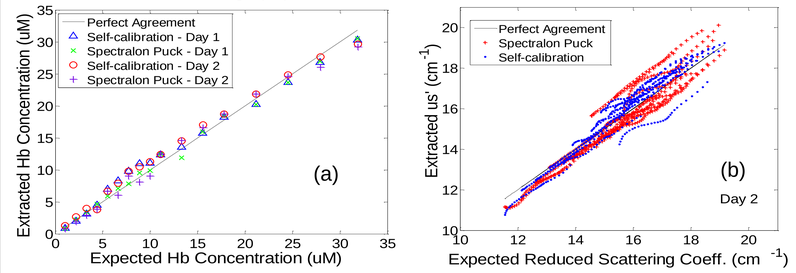


Fig. 10. Same day data analysis. Extracted v.s. expected: (a) Hb concentrations from phantom studies in two different days and (b) reduced scattering coefficients for all phantoms from Day 2 at all wavelengths from 450-600nm (similar for Day 1). *Phantom #14 from the same day was used as reference*.

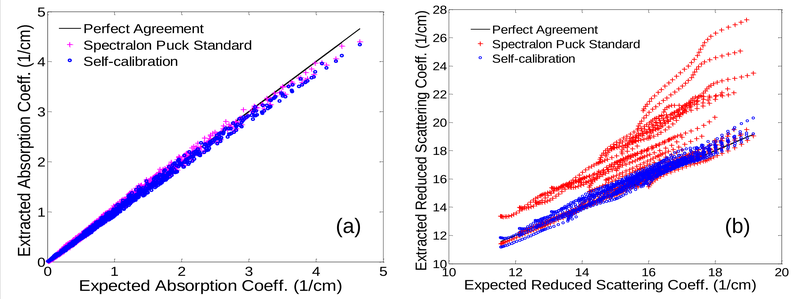


Fig. 10. Combined data analysis. Extracted v.s. expected: (a) absorption and (b) reduced scattering coefficients at all wavelengths from 450-600 nm for all phantoms from both days. *Phantom #14 from Day 1 was used as reference*.

Table 1. Comparison of accuracy of the self-calibration and standard calibration methods for extraction of phantom optical properties.

Reference Phantom 14	Spectralon Puck Standard			Self-Calibration		
	Day 1	Day 2	Combined	Day 1	Day 2	Combined
Error in μ_a	6.3±3.7%	11.3±7.0%	6.2±3.1%	6.5±3.3%	10.5±6.8%	6.3±2.6%
Error in μ_s'	2.1±2.1%	3.3±2.1%	11±10.6%	1.6±1.4%	2.9 ±2.0%	2.2±1.4%

9. Conclusions

- We have demonstrated the feasibility of performing DRS using a compact self-calibrating fiber optic probe.
- The technique can effectively correct for instrument and probe responses, short- and long-term lamp fluctuations, and fiber bending loss.
- Most importantly, it removes the need of instrument warm-up and additional calibration measurements in the clinic, therefore saves 40-60 minutes of precious clinical time.
- We have also found that scattering is more sensitive to instrument fluctuations caused by the lamp or fiber bending.
- Combined with a one time, single-reference phantom measurement, the self-calibrating probe can provide instrument-independent optical properties.

References

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Acknowledgement

- Funding for this project was provided by the NIH grant R01CA100559-01A1 and DOD BRCP Era of Hope Scholar award, both to Dr. Nimmi Ramanujam.