A fast versatile instrument for dynamic optical tomography

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Abstract: Instrumentation suitable for acquiring fast (up to 150 Hz) multi–source, multi–detector optical measurements from tissues having arbitrary geometries is described. The design rationale and measured performance features of first– and second–generation systems are given. Also shown are representative images derived from experimental studies.
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1. Introduction

Recently we have described the desirability of performing fast tomographic measurements for tissue studies [1]. Two factors motivating this are the expected influence of vascular reactivity on image quality and the wealth of new information relatable to tissue perfusion states that could be derived from the analysis of time–series image data. In this report, we focus on instrumentation design strategies that enable fast data collection. Several new design features are introduced that serve to extend a previously described instrument [2].
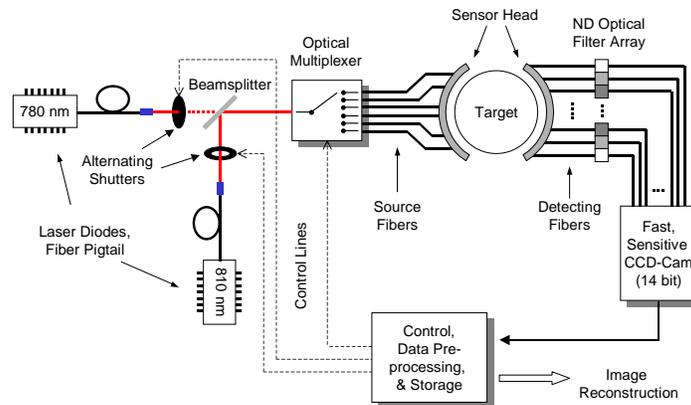
2. 1st Generation Instrument

Fig. 1. Schematic of 1st generation instrument used for dynamic optical tomographic imaging.

Figure 1 shows a block diagram of our first–generation system used for dynamic imaging studies. Briefly, the instrument functions as an alternating–source, multi–channel, parallel detection device. Major system components include light sources and power supply, an optical multiplexer employing electronic shutters, coupling optics and a stepper motor, sensor head(s), and a home–built variable attenuator and an area detector. Parallel measurements are performed by bringing optical fibers, originating from the sensor head, into contact with the front face of a 7×7 cm fiber taper bonded to a CCD array. The measurement speed is currently limited by the read time of the CCD camera. Using short acquisition times (<50 ms), data collection is restricted to ~4 Hz for studies involving a single wavelength of light, or 2 Hz for dual–wavelength measurements. The dynamic range of measurement is nominally restricted to the performance capabilities of the CCD array (*i.e.*, 14 bits). This range can be extended considerably by use of a variable attenuator. The attenuation value employed is graded with expected light levels. The attenuation applied to light captured by fibers surrounding the source fiber bundle is highest, and it decreases to zero for light captured by fibers at increasing distance from the source. Typical measurements have a dynamic range on the order of 10^8. The number of fibers contained in the sensor head varies with sensor head design (see below). Wavelength multiplexing is achieved by actuating electronic shutters under computer control in an alternating fashion. Source multiplexing is performed by using a stepper motor to reposition beam steering optics to transmitting fibers positioned in a circular array.

3. Sensor Head Design

A critical element of the system is the sensor head. Three different designs have been developed to allow for measurement of different body structures (mainly the limbs and breast), and all are geometrically adaptive in some manner.

Iris: This unit is intended for examination of structures, such as limbs, that can readily be made to adopt a cylindrical shape. It consists of a mechanical iris to which are attached optical fibers that direct and collect light from the target. The unit houses 18 fiber bundles positioned uniformly about a circle at 20° intervals. Room for additional 18 fibers is available. The pass–through diameter of the iris is continuously adjustable over a range of 3–13 cm. Optical fibers housed in the iris are bifurcated at the target end. End–on inspection of the bundle shows that the transmitting fibers are positioned in the center of a halo of receiving fibers. The receiving bundle is 3 mm in diameter and terminates at the variable attenuator. The length of each arm of the bundle is 8′. While adjustable, the iris unit is quite rigid. This serves to mechanically stabilize a target under examination against motion artifacts, while gently conforming its external geometry (*e.g.*, a forearm) to a circle.

Pad: This device was constructed for investigations of structures that are too thick to permit transmission measurements. It contains 18 bifurcated transmitting/receiving fiber bundles and 45 receiving–only bundles arranged in a 7×9 array. The unit, which is flexible in both dimensions, can be grabbed from each end and pressed against a target. Optical fibers are held in place by a serrated black rubber belt, commonly used in automobiles, through which were machined holes to contain the optical fibers. Significantly increased flexibility was achieved by removing rubber between each pair of "links." As with the iris measuring head, optimal use of this device requires use of a variable attenuator to extend the nominal dynamic range of the CCD camera. Here we use a two–dimensional array whose position is adjusted in accordance with the position of the illuminating source. This is positioned between a mount housing fibers that collect light from the pad and the front face of the fiber taper–CCD assembly. To improve coupling efficiency, the distance separating the mount and taper is <1.5 mm. The surface area of the fiber taper is sufficient to measure all 63 detecting fibers in parallel.

Folding Hemisphere: In an effort to retain the natural contour of the breast we have adopted a folding–geometry structure based on a trapezoidal icosatetrahedron. Similar to the iris design, the unit retains a fixed geometry, (*i.e.*, a hemisphere) at all diameters. The unit consists of a folding iris attached to which are additional out–of–plane folding structures that form eight evenly spaced hemispheric arcs. Adjustment of the measuring volume without interference from the fibers is accomplished by passing these through the seventeen major vertices and, if needed, twelve minor vertices formed by the hemispheric arcs. If required, additional fiber bundles can be attached between the folding structures. The diameter of the hemisphere is continuously adjustable over a range of 5–20 cm.
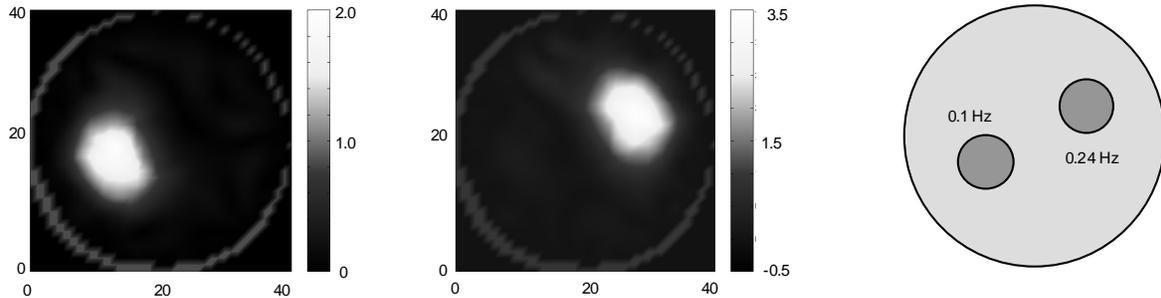

Fig. 2. Dynamic phantom studies. a) Amplitude map of FT at 0.1 Hz, b) Amplitude map of FT at 0.24 Hz, c) Schematic of phantom geometry.

Figure 2 shows a representative image obtained from a dynamic phantom study using the iris. Imaged are two balloons (~1 cm dia.) attached at both ends to a support structure oriented parallel to the vessel axis and positioned symmetrically about its center. Each was filled with 3 ml of 50 μM hemoglobin and subjected to harmonic variation in its volume (~30%) at different frequencies (0.1 and 0.24 Hz) by pneumatic displacement of the fluid from an attached reservoir. The balloons and support structure were placed inside a 7.6 cm diameter (7.3 cm ID) white Delrin® vessel containing 500 ml of 2% Intralipid®. The images shown are amplitude maps at the different beat frequencies computed from the reconstructed time–series image data. Nearly perfect temporal and spatial resolution is achieved.

4. 2nd Generation Design

Clinical applications of the above system are chiefly limited by the slow speed of source multiplexing and read rate of the CCD camera. We have addressed these issues and others by redesigning the detector module to allow for

detection of light from a modulated source. These are described in more detail elsewhere [3]. The working principle is shown schematically in Figure 3. Instead of the CCD array, we use a single photodetector channel for each fiber. The detector itself is a Si–photodiode (PD). The generated photocurrent is subjected to two amplification stages, the first of which performs a current–to–voltage conversion, and the second a further voltage amplification. Digitally addressable switching of gain factors allow for fast adaptation of the sensitivity to a large range of light levels. We furthermore introduce lock–in (LI) detection, and for this reason the laser diodes are modulated in the kHz range. This not only serves to reduce interference from electronic noise, but also rejects ambient light signals. It is further possible to detect light from more than one wavelength source simultaneously. Every detector channel contains a sample–and–hold (S/H) circuit to provide exact timing. The signals are read out and digitized using a 64 channel/16 bit PCI data acquisition board.
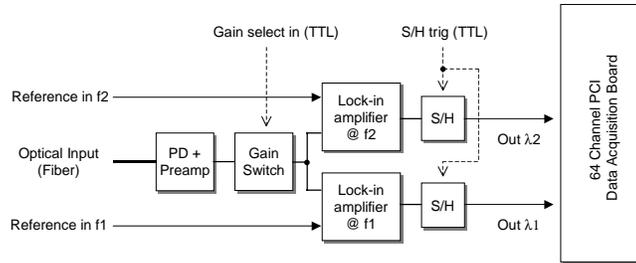

Fig. 3. Schematic drawing of the layout of one detector channel, shown for the case of dual wavelength measurement.

We have built a single–channel prototype containing one LI amplifier in order to validate the desired performance features. Our goal was to meet the following specifications: sensitivity <100 pW, linear dynamic range ≥10^7, data acquisition rate ≥60 Hz (10 Hz @ 6 source positions), possibility of working under daylight conditions. Table 1 lists the results of our tests. We also found that working in ambient light is possible. The most sensitive measurements are compromised by fluorescent lighting, but they can be performed under dimmed daylight or incandescent illumination. Figure 4 shows that the system has a linear response throughout its measuring range.

Table 1. Measured performance of a detector channel prototype

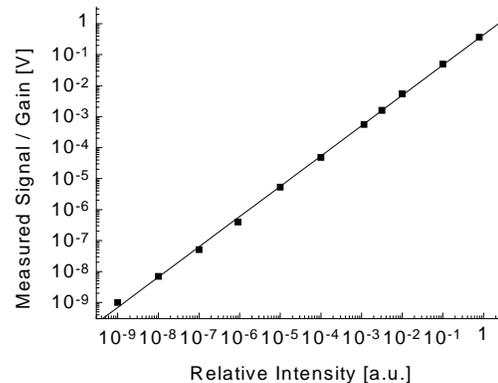| Parameter	Value
Modulation frequency	5–10 kHz
Detector settling time	5–10 ms (to 5 – <1%)
Data acquisition rate	150 Hz
Noise equivalent power	~10 pW (rms)
Dynamic range	1 : 10^9 (180 dB)
Long term stability	~1% over 30 min

Fig. 4. Measured linear response of a detector channel

5. Conclusion

We have developed instrumentation suitable to perform fast tomographic optical measurements from tissues having arbitrary geometries. Clinical testing of the new module with the various measuring heads is currently underway.

6. References

[1] R. L. Barbour *et al.*, "Optical Tomographic Imaging of Dynamic Features of Dense Scattering Media," 1999 JOSA–A, submitted.
[2] R. L. Barbour *et al.,* "Development and Evaluation of the IRIS OPTI Scanner, a General Purpose Optical Tomographic Imaging System," OSA TOPS vol. 21, p. 251–255, 1998.
[3] C. H. Schmitz *et al.*, "Instrumentation and Calibration Protocol for Imaging Dynamic Features in Dense Scattering Media by Optical Tomography," JOSA–A, submitted.

7. Acknowledgement