# Depth of arterial oscillation resolved with NIRS time and frequency domain

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**Abstract:** We investigated the depth of systemic oscillations, as the heartbeat, always present in the optical signal. To this aim we performed measurements in the head of humans and piglets using frequency domain and time domain systems. Measurements in piglets and Monte Carlo simulations have also been used towards explaining the experimental data. Preliminary results indicate that with time and frequency domain we are able to isolate the heartbeat contribution originated from intracranial layers (brain).

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## 1. Introduction

Nearinfrared spectroscopy (NIRS) in the wavelength range from 650 to 950 nm achieves sufficient photon penetration depth for noninvasive probing of brain hemodynamic in humans. Noninvasive optical measurements of brain oxygenation and functional activity are performed in both adults and neonates. Systemic oscillation such as arterial pulsation, respiration, and Mayer waves perturb the optical signal, are often considered clutter, and are eliminated with temporal and spatial filters. Nevertheless, studies have shown that important information about physiology can be extracted from these oscillations. For example, pulse oximetry uses the light changes due to heartbeat oscillations to measure arterial oxygenation ($SaO_2$) [1,2]. Similarly, respiration-induced oscillation have been proposed to be used towards measuring venous oxygenation ($SvO_2$) [3,4]. And from the shape of the heartbeat oscillations it has been proposed to measure blood velocity[5,6]. While $SaO_2$ is a systemic parameter independent from the location in which it is measured, both blood velocity and $SvO_2$ reflect the local blood flow (BF) and oxygen consumption (OC). Monitoring of cerebral BF and OC can be crucial to some patients including critically ill infants. In general, diffuse reflectance measurements from the head contain signal from both superficial layers (scalp and skull) and deeper layers (brain). Therefore, a method for separating the intracranial signals from the extra-cranial clutter is required.

In the experiments presented here, we use two instruments, both of which measure signals from the intracranial volume: a frequency domain (FD) and a time domain (TD) system. We compare the results at different distances and different time delays with Monte Carlo simulation in a 3D segmented head.

## 2. Experimental setup

We used an FD system (Imagent, ISS, Inc.) that operates at a modulation frequency of 110 MHz and at 2 discrete wavelengths (690nm and 830nm). The light sources (laser diodes) are electronically multiplexed to time share the 4 parallel detectors. The fibers from the two light sources (400 μm in diameter) are grouped into one fiber bundle (source fiber) that delivers light to tissue. The optical signal detected at the tissue surface is guided to the 4 detector channels by 4 fiber optic bundles (detector fibers 3 mm in diameter). The sampling rate for the measurement when there are 2 wavelengths and 4 detectors is 50Hz. The source and the detector fibers were placed on the same side of the examined tissue for each measurement (forehead in humans, left side of the head in piglets). The detector fibers were placed at 1.0, 1.5, 2.0 and 2.5 cm from the source fiber. We also used a TD system based on a pulsed Titanium-Sapphire laser and an image intensified CCD camera to perform heartbeat measurements in humans. The TD probe consists of one source and 3 detectors placed at 1, 2 and 3 cm from the source. Each detector location consists of 6 fibers of different lengths to allow for detection of light at different delays (at the time the image is taken with the CCD camera photons arriving from longer fibers have shorter delays than photons arriving from shorter fibers). This probe geometry allows us to collect light using six different time delays simultaneously at each detector fiber position (delays ranging from 0 to 3 ns in steps of 500 ps). The measurement sampling rate of this system (1 wavelength, 3 detector positions, and 6 time delays per detector) was 12 Hz. With both systems the arterial oscillations were recorded synchronously with a pulse oximeter.

For the measurements of the heartbeat in humans, we collect data for 2 minutes with the FD system, followed

by a measurement of 10 minutes with the TD system with the probe in the same location on the forehead. The FD data was low-pass filtered at 25Hz, and the slope and intercept values for phase and amplitude were calculated using the multi-distance scheme [10]. TD data was high-pass filtered (0.2Hz) to remove the slow drifts, and low-pass filtered (3Hz) to remove high frequency noise. In both cases the heartbeats were block averaged using the onsets given by the pulse oximeter signal.

The rationales for our measurements are as follows:

1. Experiments with bilayered phantoms have shown that using the FD multi-distance method and sufficient source detector separation (more than 1 cm) ensures that the measured optical properties are representative of the deeper layer when the superficial layer is less than ~5 mm in thickness [7]. This can be due to the lower sensitivity of the slope to superficial layers. With the frequency-domain measurements we wanted to see if the shape of the heartbeat is different for amplitude (ac), phase at different source-detector separations, and for their slopes and intercepts. This can be the case if the blood velocity is different in the scalp and in the brain and if different measured parameters are sensitive to different depths. We took advantage of the fact that the frequency domain system acquires at a fast rate (50Hz) and we can average many heartbeats in 2 minutes to increase the SNR.

2.Time domain measurements at different time delays give information about photons that have traveled different distances in the tissue. Longer delays should correspond with photons that traveled (on average) through deeper layers. While changes in absorption in a superficial layer will affect the light detected at all of the time delays in the same way, changes in absorption in deeper tissues should affect more strongly the light detected at longer delays.

Monte Carlo simulations in a 3D human head were performed to compare the results in the TD and FD systems, by varying the absorption selectively in different layers (namely, scalp, skull, and brain) [8].

### 3. Results-Discussion

Figure 1 shows the average heartbeat measured on the forehead of one healthy adult for 2 min with the FD system. The amplitude (ac) (panel a) and phase (panel b) measurements at different distances and the slopes and intercepts for 830 nm are displayed normalized between 0 and 1 for comparison. The heartbeat is clearly detected from progressively lower SNR. The shape of the amplitude (ac) signal is different for the slope than for the single distance and the intercept, suggesting that it originates from different layers.

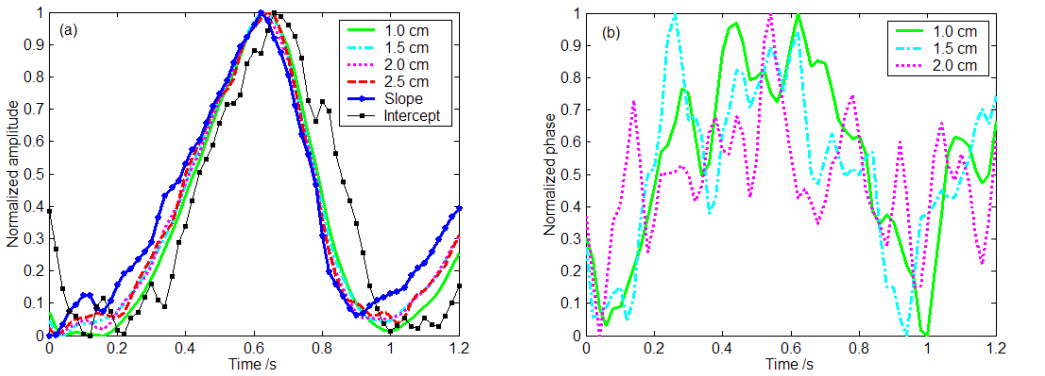


Fig. 1: Average heartbeat measured with the FD system in humans: ac (a) and phase (b).

We repeated these measurements in newborn piglets, which have a much thinner scalp and skull than adult humans. In this case the heartbeat signal for ac, ac slope, and ac intercept predominantly comes from the deeper layer (brain). We verified this by performing ICG bolus injection and observing a fast recovery time which is the expected results for brain tissue [9]. For the heartbeat measurements in piglets (Fig. 2), the shape difference observed in humans does not exist.

The TD results obtained on the same subject as in Fig. 1 are shown in Figure 3 for a probe having a source-detector separation of 3 cm to have 6 delays. Other distances showed similar results. Figure 3a shows the average of the heartbeats obtained during a 10 min measurement for the 6 different delays. The heartbeat is clearly visible with an average frequency of 1.2 Hz. Figure 3b shows the amplitude of the heartbeat as a function of the delay. We observe a clear increase in the signal with later delays.

In order to interpret this result, we performed Monte Carlo simulations on a segmented head with four tissue types: scalp ($\mu_a$=0.19cm$^{-1}$, $\mu_s$'=6.7cm$^{-1}$), skull ($\mu_a$=0.14cm$^{-1}$, $\mu_s$'=8.6cm$^{-1}$), cerebrospinal fluid ($\mu_a$=0.04cm$^{-1}$, $\mu_s$'=0.1cm$^{-1}$), and brain ($\mu_a$=0.2cm$^{-1}$, $\mu_s$'=11.1cm$^{-1}$). The temporal point spread function between 0 and 4 ns was

calculated. We successively simulated a 1% variation in the absorption of each layer and calculated the induced change in the signal for all 3 cases. In the case of an absorption change occurring in the scalp or in the skull, we observed that the induced contrast was almost independent of the delay. On the contrary, for an absorption change in the brain, we observed a significant increase in the contrast with late delays. This variation of the contrast as a function of the delay is very similar to what we observed experimentally (Fig.3b). This result supports the hypothesis that late time delays detect a heartbeat signal that is mostly originating from the brain.

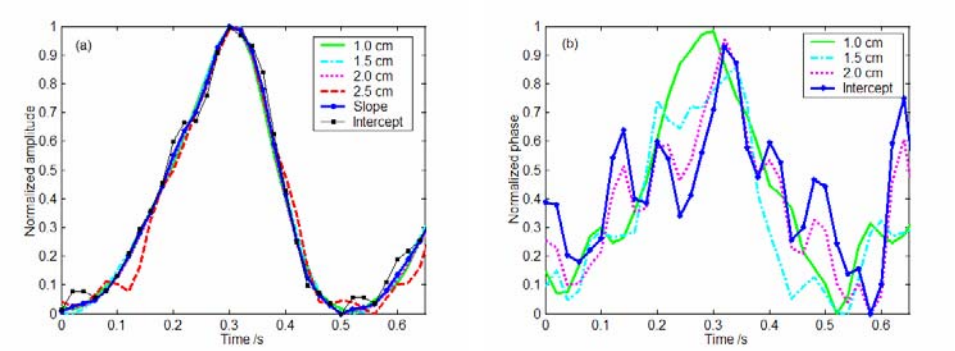


Fig. 2: Average heartbeat measured with the FD system in a 7 days old piglet: ac (a) and phase (b).

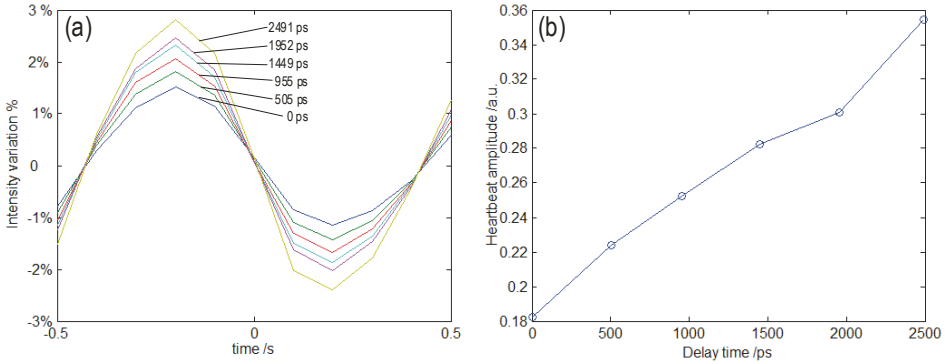


Fig. 3. (a) Average heartbeat measured with TD system for different delays, (b) Heartbeat amplitude measured with the TD system vs delay.

## 4. Summary

The results presented here indicate that both FD and TD systems are capable of detecting the intracranial heartbeat signal. Moreover, these results suggest that appropriate selection of the experimental conditions (probe geometry, TD delay) can increase the sensitivity of the systems to signals originating from deeper layers.

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