Cerebral Monitoring in Cardiac Surgery with Near-Infrared Spectroscopic (NIRS) Diffuse Optical Tomography (DOT)

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I. Introduction

- Cerebral perfusion and oxygenation is an important clinical parameter
- Neurological complications remain prevalent after cardiac surgery, due to inadequate perfusion [1]
- Currently available FDA approved devices providing non-invasive monitoring of cerebral oxygenation are based on low density transmitter/sensor configurations providing limited oximetry sampling of a small volume of the frontal cerebral cortex [2]
- It is uncertain whether such limited sampling is representative of regional cerebral perfusion which is supported by a complex vasculature architecture
- The aim of this study is to determine whether low density optical sensor arrays are sufficient to accurately detect dynamic responses of intraoperative cerebral perfusion in patients undergoing cardiac surgery

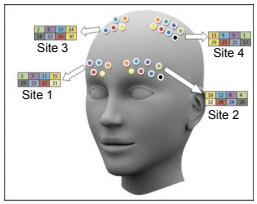

Figure 1. Geometrical configuration of the four optode arrays.

II. Methods

- 6 adult patients undergoing various non-emergency cardiac surgical procedures were recruited for this study (Table 1)
- A multi-channel continuous wave near-infrared optical tomography imager (DYNOT System, NIRx Medical Technologies, LLC., Glen Head, NY) was utilized
- The optodes are attached to a conforming helmet and arranged in arrays covering 4 sites: frontal and prefrontal cortex of the left and right hemispheres (Figure 1)
- Two wavelengths of light (760 nm and 830 nm) are used for imaging, and a complete scan of the array is accomplished in approximately 125 milliseconds
- Concurrent with the optical measurement, physiologic parameters [e.g., mean arterial pressure (MAP), pulmonary artery pressure (PAP)] and maneuvers by the surgical and anesthesia team (e.g., position change of patient) are recorded
- Raw optical data are preprocessed by low-pass filtering to remove high-frequency noise and cardiac and respiratory fluctuations, a maximum coefficient-of-variation threshold is applied to remove excessively noisy data channels; and data are normalized to compensate for differences in detector efficiency and amplifier gain [3]
- Oxy-, deoxy-, and total hemoglobin time series are computed for the each data channel [3]; volumetric images are reconstructed by the Normalized Difference Method [4] applied to a segmented finite element model (FEM) mesh
- Hemoglobin time series are organized into groups based on the source-detector (channel) distance
- For each channel-distance subgroup, spatial mean and spatial standard deviation time series are calculated and compared within and between the array sites
- Correlation coefficients are computed between pairs of large-distance channels, to determine intra-site and inter-site variability during the entire measurement period and over selected hemodynamically significant events
- The range of changes in hemoglobin concentration during hemodynamically significant events are calculated, and the probability of failure to detect the event by individual channels are computed, as a function of the threshold value.

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III. Results

Patient	Gender	Age	Co-morbidities	Surgery	Hemodynamic Event
1	F	65	HTN, DM, CAD	CABG - Off-pump converted to on-pump beating heart	12500:13000 V-fib arrest/ crash on CPB
2	F	73	HTN, DM, COPD	CABG - Off-pump	15500:16500 V-fib / Cardioversion
3	M	67	HTN, CHF	AVR - On-pump	2500:3500 Initiation of CPB
4	F	58	HTN, DM	CABG - On-pump	5000:7000 Initiation of CPB
5	F	58	HTN, DM, CHF	CABG - On-pump	6500:8500 Initiation of CPB
6	F	27	HTN, ESRD, SLE	AVR - On-pump	8000:11000 Initiation of CPB

Table 1. Patient demographics, surgical procedures, and clinically significant event analyzed.
HTN = hypertension, DM = diabetes mellitus, CAD = coronary artery disease, COPD = chronic obstructive pulmonary disease, CHF = congestive heart failure, ESRD = end-stage renal disease, SLE = systemic lupus erythematosis, CABG = coronary artery bypass grafting, AVR = aortic valve replacement, V-fib = ventricular fibrillation, CPB = cardiopulmonary bypass.

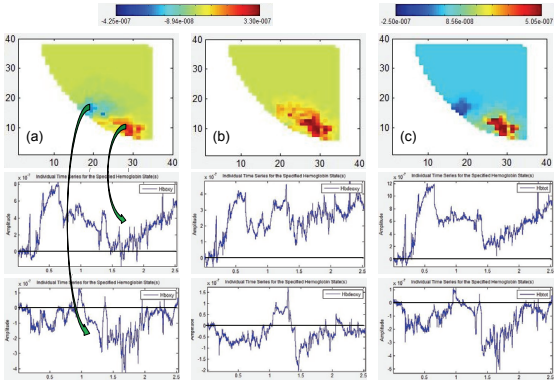

Figure 2. Top row: representative 2D sections (axial) through a 3D reconstructed image of the right frontal cerebral cortex, patient 1, during V-fib arrest; (a) ΔHb_{oxy}, (b) ΔHb_{deoxy}, (c) ΔHb_{total}; units (colorbar) are molar concentration. Second and third rows: reconstructed ΔHb_{oxy}, ΔHb_{deoxy} and ΔHb_{total} time series, in the indicated volume elements, over the complete measurement time course (about 5 hours).

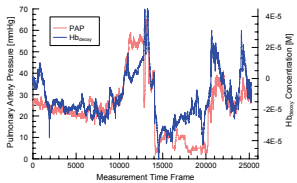

Figure 3. Pulmonary artery pressure time series (red curve) from invasive concurrent physiological monitor (Swan-Ganz catheter) plotted together with the single detector-channel time series (blue curve; ΔHb_{deoxy}, Site 3, source-detector separation = 2 cm) that is most strongly correlated (r = 0.75) with PAP.

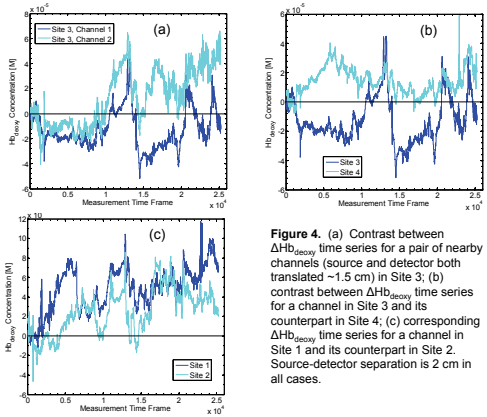

Figure 4. (a) Contrast between ΔHb_{deoxy} time series for a pair of nearby channels (source and detector both translated ~1.5 cm) in Site 3; (b) contrast between ΔHb_{deoxy} time series for a channel in Site 3 and its counterpart in Site 4; (c) corresponding ΔHb_{deoxy} time series for a channel in Site 1 and its counterpart in Site 2. Source-detector separation is 2 cm in all cases.

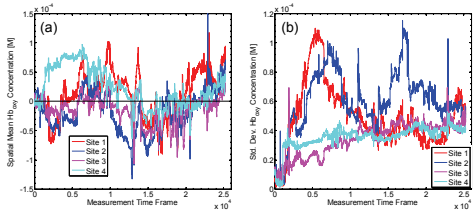

Figure 5. (a) Spatial mean ΔHb_{oxy} time series at each of the four measurement Sites, for channels with source-detector separation distances ≥ 3 cm; (b) corresponding spatial standard deviation ΔHb_{oxy} time series for each of the four measurement sites.

Subject	PAP/Deoxy Corr.	Intra-site Corr. Complete	Intra-site Corr. Hemodynamic Event	Inter-site Corr. Complete	Inter-site Corr. Hemodynamic Event
1	-0.400 +0.753	+0.517 (Site 4) +0.966	+0.220 (Site 4) +0.990	-0.0843 (Sites 3,4) +0.725	-0.0641 (Sites 2,4) +0.935
2	-0.694 +0.536	+0.184 (Site 1) +0.988	+0.364 (Site 3) +0.990	-0.0190 (Sites 3,4) +0.899	-0.00440 +0.954 (Sites 3,4)
3	-0.445 +0.587	-0.0368 (Site 4) +0.994	-0.135 (Site 4) +0.998	-0.0510 (Sites 2,4) +0.982	-0.0408 (Sites 3,4) +0.994
4	-0.838 +0.953	+0.0655 (Site 1) +0.994	+0.203 (Site 4) +0.973	-0.562 (Sites 1,3) +0.888	-0.0498 (Sites 3,4) +0.739
5	-0.899 +0.757	-0.457 (Site 4) +0.996	+0.389 (Site 4) +0.997	+0.0560 (Sites 2,4) +0.905	0.0313 (Sites 2,4) +0.985
6	-0.918 +0.869	-0.259 (Site 1) +0.928	-0.0739 (Site 1) +0.992	-0.0985 (Sites 1,3) +0.967	-0.0205 (Sites 1,3) +0.959

Table 2. Ranges of observed correlation coefficients, for channels with source-detector separation distances ≥ 3 cm: (Column 2) between hemodynamic time series and the PAP recording; (Columns 3-6) between pairs of hemodynamic time series.

Subject	Threshold ΔHb/ Max. ΔHb-oxy (50%)	Threshold ΔHb/ Max. ΔHb-oxy (10%)	Threshold ΔHb/ Max. ΔHb-deoxy (50%)	Threshold ΔHb/ Max. ΔHb-deoxy (10%)	Threshold ΔHb/ Max. ΔHb-tot (50%)	Threshold ΔHb/ Max. ΔHb-tot (10%)
1	56.9	41.2	44.9	18.4	13.4	3.0
2	42.9	19.1	16.7	-51.5	36.2	6.9
3	21.3	11.9	19.4	3.5	28.2	4.3
4	42.1	-23.7	0	-39.3	54.4	-8.5
5	56.5	23.2	64.2	13.3	49.3	17.4
6	23.8	6.8	21.1	12.1	-26.9	-50.0

Table 3. Required percent reduction in threshold value in order to achieve the indicated single-channel false negative rates (FNR; FNR = 100 – Sensitivity), when the magnitude of the observed change in ΔHb is used as a monitor for clinically significant events (Table 1), for channels with source-detector separation distances ≥ 3 cm.

IV. Conclusions

- Intra-operative regional cerebral perfusion is highly heterogeneous
- Minor changes in source/detector pair location result in notably different signal recordings.
- Low density source/detector configurations currently used to delineate regional cerebral oxygenation intra-operatively are unlikely to provide accurate representation of cerebral perfusion or to detect hemodynamically significant events

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