Cerebral Oximetry Neglects Variability of Cerebral Perfusion During Cardiac Surgery

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Introduction

- Cerebral oxygenation and perfusion are important clinical parameters, since hypoxia is the primary cause of neurological injuries [1].
- These parameters may help guide intraoperative monitoring during procedures associated with neurological complications [2,3].
- While stroke and cognitive dysfunction are complications of many surgical procedures, the incidence following cardiac surgery remains highest [4,5]. Consequently, prompt identification of cerebral hypoxia before irreversible injury occurs is paramount.
- Devices currently approved by the Food and Drug Administration (FDA) provide non-invasive monitoring of cerebral oxygen saturation based on low-density configurations of transmitters and sensors [6-8].
- Intraoperative cerebral monitoring using cerebral oximetry, coupled with intervention to keep brain oxygen saturation above a fixed threshold, has not significantly reduced the incidence of stroke following cardiac surgery [9].
- Given the heterogeneity of cardiac surgical patients, who commonly present with one or more pre-existing risks (e.g., hypertension, diabetes, cerebral / coronary / peripheral atherosclerotic disease), it is uncertain whether oximetry based on sampling small areas over the frontal lobe is representative of regional cerebral perfusion.
- In this study we have explored whether low-density optical sensor arrays, derived from small subsets of four larger arrays, are able to provide representative measures of the true state of regional cerebral perfusion in patients undergoing cardiac surgery.

Methods

- Data from six participants in an intraoperative cerebral monitoring study were analyzed (Table 1).
- Optodes were attached to a headgear and arranged in arrays covering 4 sites (Fig 1).
- Optical recordings and a record of intraoperative events were taken during surgery using a Near-Infrared Spectroscopic (NIRS) imaging system (NIRx DYNOTcompact). The data were examined retrospectively to identify clinically significant events.
- An anesthesia monitor (Dräger-Narkomed 6000) was used during surgery to simultaneously measure physiological parameters such as mean systemic arterial and pulmonary arterial pressures.
- A global estimate of light-source intensity variability and superficial hemodynamic fluctuations was computed, and least-squares linear regression was used to subtract the contribution of the global factor from each raw data time series [10].
- The normalized difference method [11] was used to recover time series of volumetric images from the pre-processed data (see Fig. 2).
- Analysis of hemoglobin (Hb) levels was performed using a modified Beer-Lambert law (MBL) [12] algorithm to compute time series of oxy, deoxy and total Hb (Hb_{oxy}, Hb_{deoxy}, Hb_{total}) for all channels.
- Superficial-signal correction was carried out for each channel as depicted in Fig 3. Channels labeled S1D4 and S4D1 are a reciprocal pair, with the roles of S and D interchanged.
- The signals measured contain cerebral and overlying tissue contributions. In contrast, channels S1D3 and S4D2 consist largely of signals from overlying tissue. This would appear to allow for selective removal of the superficial-tissue component of the data recorded by the S1D4 and S4D1 channels [13].
- Correlation coefficients are computed for all pairs of channels having the same S-D separation distance (see Fig. 4).
- The superficial-signal corrected time series of Hb_{oxy}, Hb_{deoxy}, & Hb_{total}, for all channels with S-D separation ≥ 3cm, were compared in regard to the magnitudes of the detected Hb concentration changes. A large, relatively abrupt change in Hb level is taken as an indication that a clinically significant event is occurring (see Fig. 5(a)). The overall sensitivity—i.e., percentage of S-D channels that report the clinically significant event—was calculated, as a function of the trigger level (see Fig. 5(b)).

Subject	Gender	Age	Surgery	Measurement Duartion	Hemodynamic Event
1	F	65	CABG – Off-pump converted to on-pump beating heart	5h 18m	VF arrest / crash on CPB
2	F	73	GABG – Off-pump	5h 38m	VF / Cardioversion
3	M	67	AVR – On-pump	3h 00m	Cardiac Cannulation
4	F	58	GABG – On-pump	4h 32m	Initiation of CPB
5	F	58	GABG – On-pump	3h 27m	Low CPB flow rate
6	F	27	AVR – On-pump	4h 44m	Retrograde Autologous Priming of CPB

Table 1. Clinical information for the study participants. Abbreviations: AVR = aortic valve replacement, CABG = coronary artery bypass graft, CPB = cardiopulmonary bypass, VF = ventricular fibrillation.

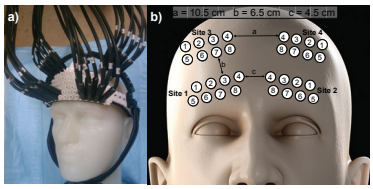

Figure 1. a) Photograph of headgear with the four-site optode array; b) Diagram of the optode arrangements in each site, and their inter-site distances.

Results

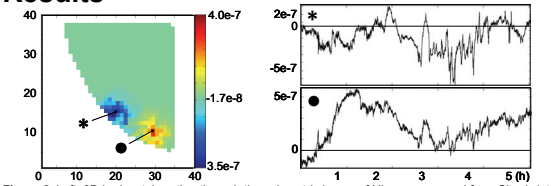

Figure 2. Left: 2D horizontal section through the volumetric image of Hboxy, recovered from Site-1 data collected near the 2.5-hr mark, for one of the study participants. Right: time series of the recovered Hboxy concentrations (time-varying perturbations with respect to a baseline mean value) in two selected pixels, labeled by the '*' and '•' symbols.

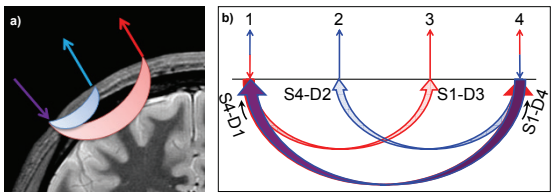

Figure 3. a) Cartoon illustrating the principle of the small-array cerebral oxygenation probe: light received by the detector located closer to the source (blue) predominantly traverses a superficial volume of tissue, while the detector located farther from the source (red) receives light that passes through both extra-cerebral and cortical tissue. b) A 180° rotation of the probe consisting of S1, D3 and D4 (red arrows) transforms it into the probe consisting of S4, D2 and D1 (blue arrows).

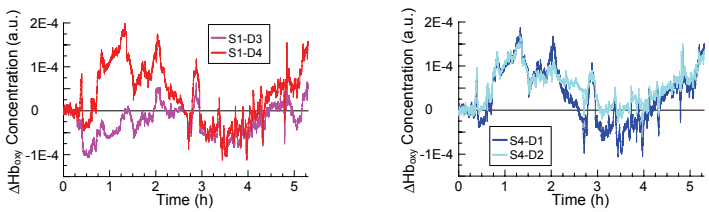

Figure 4. Hb_{oxy} time series recorded from a set of channels having the geometry depicted in Fig. 3(b). The curves for channels S1-D4 and S4-D1 (3 cm S-D separation, reciprocal pair) are nearly superimposable (r = 0.995), while the time series for S1-D3 and S4-D2 (2 cm) are substantially different.

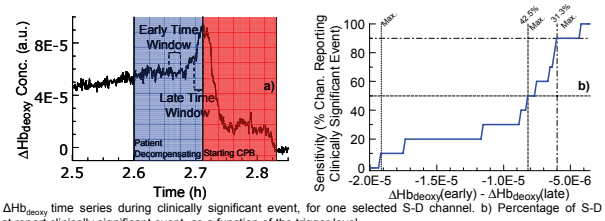

Figure 5. a) ΔHb_{deoxy} time series during clinically significant event, for one selected S-D channel. b) Percentage of S-D channels (fixed separation) that report clinically significant event, as a function of the trigger level.

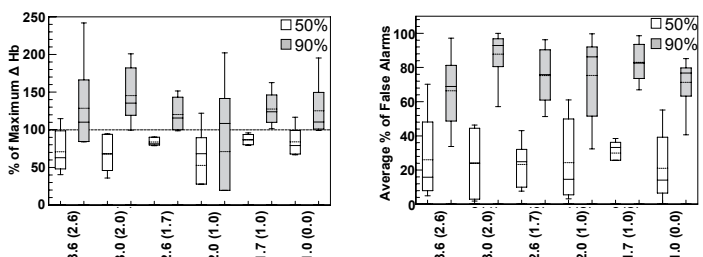

Figure 6. (a) Summary of event-sensitivity analysis (Fig. 5), for the 6 participants. The '$X(Y)$' notation indicates a detector located X cm from the source is used as a deep-tissue probe, while a detector Y cm from the source is used for superficial-tissue correction (Fig. 3). Vertical axis is the degree to which the trigger level must be reduced, relative to the subject-dependent maximum value, for the indicated % of detector channels to report a clinically significant event. Values in excess of 100% occur when the measured Hb_{deoxy} increases at some locations on a subject's scalp, and decreases at others. For each subject, the number of channels compared ranges from 10 (3.6-cm separation) to 80 (1-cm). Indicated for each box are the median (solid line) and mean (dotted) values, 1st and 3rd quartiles (rectangle ends) and extreme values (endcaps). **(b)** Summary of the corresponding false-alarm rates, computed by counting the number of channels that incorrectly report the occurrence of a clinically significant event when the trigger levels determined in the preceding step are applied to data collected during a baseline/control time interval.

Conclusion

- While subjects were under general anesthesia, their intraoperative cerebral perfusion remained highly heterogeneous.
- Minor changes in source-detector pair location result in notably differing signal recordings.
- FDA-approved non-invasive cerebral oximetry devices, based on low-density arrays, are unlikely to yield accurate representation of complex heterogeneous cerebral perfusion.
- In contrast, a tomographic imaging method with a rich array of optodes would retain the possibility to capture time-varying heterogeneous spatial maps of cerebral perfusion.

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Acknowledgements

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