Spatiotemporal Forward Model for Diffuse Optical Tomography

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QUESTIONS

What are the spatial maps and principal components of systemic effects?

The physiological variance in diffuse optical tomography (DOT) is caused by systemic and local effects. Systemic sources include cardiac pulsation, respiratory movements and Mayer waves. Local sources include vasomotion and neurovascular coupling. We want to study these components but the effects are mixed and cannot be experimentally separated without greater prior knowledge about this physiology.

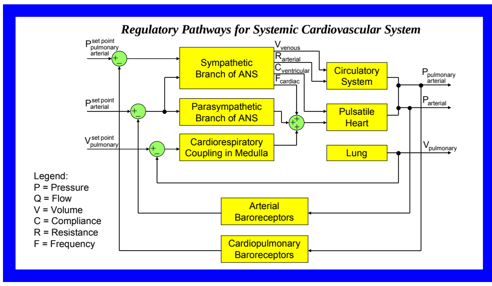
What are the transfer function models for measurable physiology?

We pose these questions to demonstrate the utility of spatiotemporal forward modeling of DOT. Our model was constructed by assembling available systemic and cerebral physiological models and biophysical models of the head for the purpose of exploring the dynamics of DOT. Here we analyze simulated DOT measurements to characterize the systemic physiological components.

FORWARD MODEL

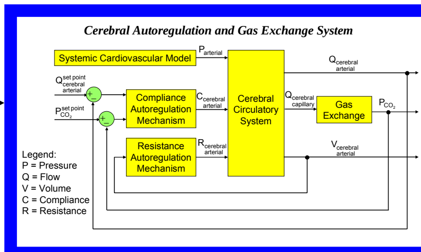
Systemic Cardiovascular System Model
This systemic physiology model includes a pulsatile heart, circulatory system, short-term regulatory system and resting physiological perturbations [1]. The circulatory system is a nonlinear, lumped parameter model. The regulatory system contains the arterial baroreflex, cardiopulmonary baroreflex and direct neurological coupling between respiration and heart rate.

Regulatory Pathways for Systemic Cardiovascular System



Arterial Blood Pressure
Including cardiac, respiratory and Mayer wave variability

Cerebral Autoregulation and Gas Exchange System



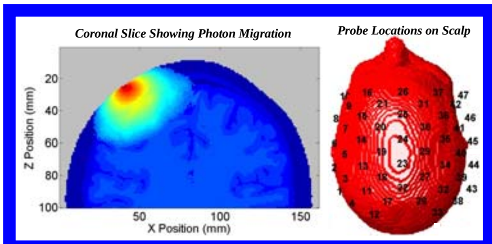
Cerebral Autoregulation and Gas Exchange Model
Arterial blood pressure from the peripheral cardiovascular model drives our cerebral autoregulation and gas exchange model adapted from Lu et al. [2]. The model consists of a nonlinear, lumped parameter circulatory model, a multicomponent tissue model of interstitial and intracellular fluid spaces and cerebrospinal fluid, a gas transport model between blood and tissue including metabolic demands, and autoregulation of cerebral blood flow.

Extracranial Hemodynamics
Arterial and venial volume and oxygenation changes

Cerebral Hemodynamics
Volume and oxygenation changes in cerebral vasculature

Photon Migration Simulator
Photon migration in the tissue was numerically modeled with a Monte Carlo simulation of the radiative transport equation [3]. Measurements were simulated on a hexagonal arrangement of 15 sources and 32 detectors on the scalp surface yielding 62 first and 52 second nearest neighbor pairs. The simulator combines the anatomical head model and the time-varying tissue optical properties. The photon migration simulator produces the dynamic DOT measurements in the same format as a real physical instrument so that the same processing stream may be used on real and simulated data.

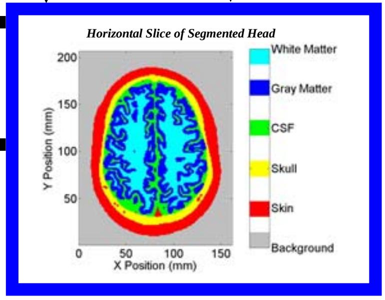
Coronal Slice Showing Photon Migration / ***Probe Locations on Scalp***



Tissue Optical Properties
Incorporating physiological dynamics and anatomical structure

Anatomical Head Model
Segmented or probabilistic map of tissue types

Horizontal Slice of Segmented Head



Digital Brain Phantom
Our digital model of the human head is an anatomical MRI segmentation that includes scalp, skull, cerebrospinal fluid (CSF), gray and white brain matter. A probabilistic digital brain phantom that further includes the inter- and extracerebral vasculature may also be used but is not shown here [4-7]. We mapped the blood gas dynamics from the physiological models to the optical properties for each voxel in the anatomical model with hemoglobin dissociation curves, estimated blood volume fractions and hemoglobin absorption coefficients.

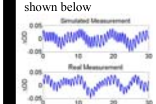
Linearized Photon Migration Model
Spatial distribution of optical pathlengths estimated from mean tissue properties

Rendered Brain Surface
Used for displaying back projected images

Simulated DOT Measurements
Wavelength, time and position dependent

Measurable Physiology
Heart rate variability, blood pressure variability and respiratory movements

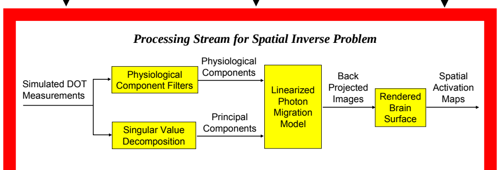
Note that simulated and real measurements qualitatively agree as shown below



INVERSE

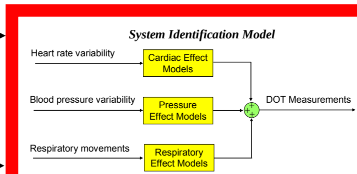
Spatial Analysis of DOT Signal Components
We separated the simulated DOT measurements into physiological and principal components using a filter bank and the singular value decomposition respectively. The spatial structures of the components are displayed by projecting the results onto a graphically rendered cortical surface with a linearized photon migration model.

Processing Stream for Spatial Inverse Problem



Spatial Activation Maps
The time series of images is a spatiotemporal representation of the measurements

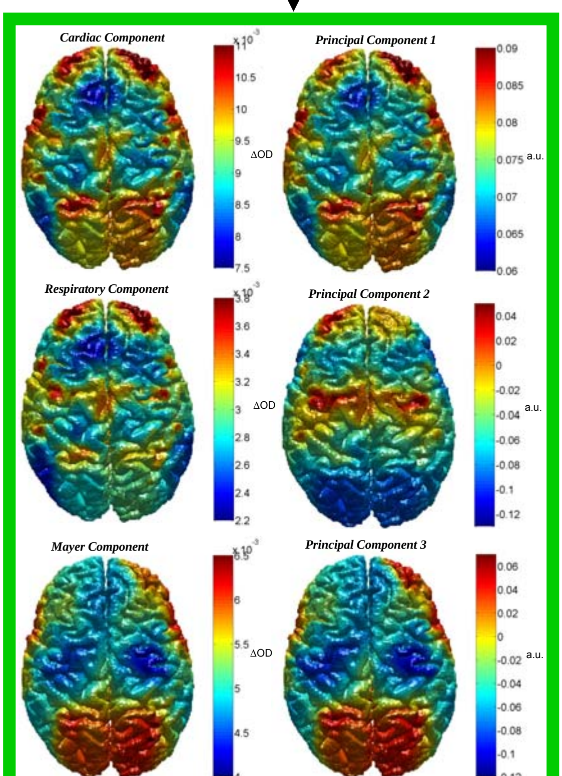
System Identification Model

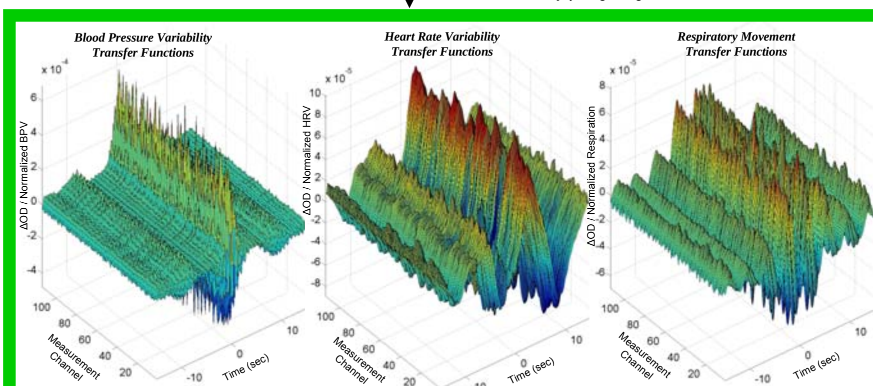


Linear System Identification
We applied a standard linear system identification approach to estimate the linear, time-invariant transfer functions that relate the measurable physiology to the DOT measurements. This model assumes that the measurements are comprised of a linear combination of transformed heart rate and blood pressure variability and respiratory movements. We estimated a separate model for each measurement channel.

Estimated Linear Transfer Functions
Models are estimated for all channels and for each of the measurable physiological signals

RESULTS





Spatiotemporal forward modeling of DOT reveals the systemic physiological effects.

The spatial activation maps of systemic physiological components show that complex spatial variation can arise from the frequency dependence of cerebral autoregulation combined with the spatial variations in DOT measurement sensitivity to different tissue types. The striking similarities between certain physiological and principal components provides insight on the blind separability of systemic effects.

The system identification transfer functions show that while the dynamic relationships between measurable physiology and DOT are generally consistent, there is considerable variation from channel to channel. These results could be used as statistical priors to improve signal separation in the analysis of real data. These time-invariant models could also be evaluated against a dynamic state-space approach to system identification.

[1] R. Mukkamala and R. J. Cohen, "A forward model-based validation of cardiovascular system identification," Am J Physiol Heart Circ Physiol 281, H2714-H2730 (2001).
[2] K. Lu, J. W. Clark, Jr., et al., "Cerebral autoregulation and gas exchange studied using a human cardiopulmonary model," Am J Physiol Heart Circ Physiol 286, H584-H601 (2004).
[3] D. A. Boas, J. Culver, J. Stott and A. K. Dunn, "Three dimensional Monte Carlo code for photon migration through complex heterogeneous media including the adult head," Optics Express 10, 159-170 (2002).
[4] D. L. Collins, A. P. Zijdenbos, V. Kollokian, J. Sled, N. J. Kabani, C. J. Holmes, and A. C. Evans, "Design and construction of a realistic digital brain phantom," IEEE Transactions on Medical Imaging, vol. 17, no. 3, pp. 463-468, 1998.
[5] R.K.-S. Kwan, A.C. Evans, G.B. Pike : "MRI simulation-based evaluation of image-processing and classification methods," IEEE Transactions on Medical Imaging. 18(11):1085-97, Nov 1999.
[6] C.A. Cocosco, V. Kollokian, R.K.-S. Kwan, A.C. Evans : "BrainWeb: Online Interface to a 3D MRI Simulated Brain Database," NeuroImage, vol.5, no.4, part 2/4, S425, 1997.
[7] http://www.bic.mni.mcgill.ca/brainweb/

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