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Evaluation of Spatially Resolved Spectroscopy (SRS) in Traumatic Brain Injury (TBI)

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Aims

- **To evaluate current SRS method on realistic 5 layered head models.**
- **To adapt SRS to work with model based numerical reconstruction.**

Introduction

Traumatic brain injury (TBI) patients require constant monitoring to guide therapy and preserve neurological tissue. Functional near infrared spectroscopy (fNIRS) has potential to provide for real time cerebral oxygenation assessment. However, accurate brain measurements are limited by signals originating in superficial skin and bone regions [1].

Equation 1 – Equation to calculate absorption coefficient, μ_a, at a given wavelength, λ, using the change in light attenuation, A, with detector separation, ρ, where, k, is an unknown constant.

$$k.\mu_a(\lambda) = \frac{1}{3(1-6.3E^{-4}\lambda)}\left(\ln(10)\frac{\delta A(\lambda)}{\delta\rho} - \frac{2}{\rho}\right) \quad (1)$$

$$\begin{bmatrix} k.HbO \\ k.HHb \end{bmatrix} = [\varepsilon_{i,j}]^{-1}\begin{bmatrix} k.\mu_a(\lambda_1) \\ k.\mu_a(\lambda_2) \\ k.\mu_a(\lambda_3) \end{bmatrix} \quad (2)$$

Equation 2 – Equation to calculate chromophore concentration from absorption coefficient, μ_a, using extinction coefficients, ε, for each chromophore at each wavelength.

Spatially resolved spectroscopy (SRS) is an algorithm (***Equ. 1 & 2***) designed to measure tissue oxygenation index (TOI) and tissue haemoglobin index (THI) in deep tissues (~2 cm depth), without contamination from superficial layers [2]. This is achieved by measuring ∂A/∂ρ; the change (gradient) in detected light over a series of multi-distance detectors (***Fig. 1A & B***).

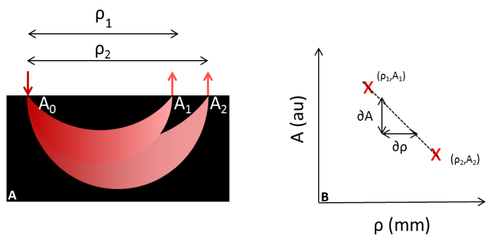

Figure 1 – A - Illustration of the spatially resolved spectroscopy measurements (A) at distance (ρ) from the source (A_0). B – Plotting gradient of measurements (A) over distance (ρ) to give ∂A/∂ρ

The ability to differentiate deep and superficial signals is paramount for TBI monitoring; after trauma, oxygenation changes in the brain no longer mirror those of somatic tissues.

Method

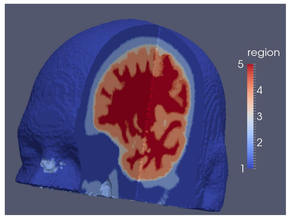

Figure 2 – 3D five layered head model used to model NIRS probes. The regions are 1 - scalp, 2 - bone, 3 - CSF, 4 - white matter and 5 - grey matter.

Table 1 – Probe Specifications

Source Wavelengths (nm)	Source-Detector spacing (mm)	No. of Measurements
735, 810, 850	37 & 43	6

Table 2 – Optical Properties

Region	HbO (mM)	HHb (mM)	HbT (mM)	H_2O (%)	S_A	S_P
Skin	0.0560	0.0140	0.070	50	0.14	2.82
Bone	0.0392	0.0098	0.049	15	1.4	1.47
Brain	0.0540	0.0220	0.076	78	0.54	0.76

Finite element model (FEM) simulations were used to model the Niro-200NX (Hamamatsu) probe geometry and source wavelengths (***Table 1***) on a realistic, 5 layered head model (***Fig 2***) with the optical properties shown in ***Table 2***. Data were simulated for saturation changes in the brain, between 80-100%, while superficial absorption remained constant. The SRS algorithm was then used to calculate TOI values for the simulated dataset.

Results - Evaluating SRS

Evaluation of the SRS algorithm considered three aspects:

Sensitivity – How does the sensitivity of SRS change in different regions of the head?
Range – How similar are the changes in TOI to the simulated 20% saturation change?
Quantitative Accuracy – How similar is the TOI value to the actual saturation?

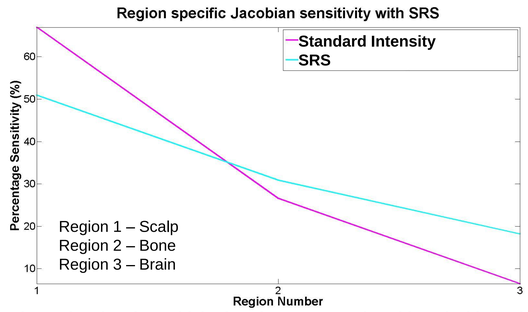

Figure 3 – Comparison of regional sensitivity for Niro-200NX probe with and without the SRS algorithm.

Sensitivity analysis confirmed that SRS has a greater response to changes in the brain region and decreased response in the scalp compared to intensity measure models (***Fig. 3***).

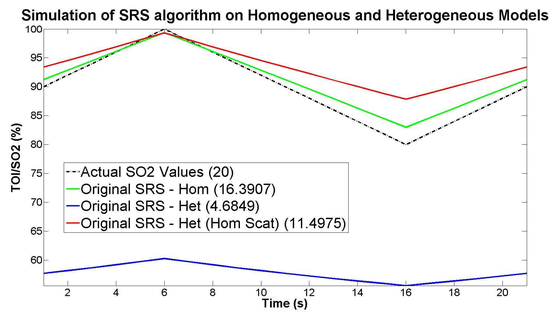

Figure 4 – Comparison of SRS performance on homogeneous and heterogeneous models using the Niro-200NX geometry on a 5 layered head mesh. TOI range values are shown in brackets in the graph legend.

Simulation findings confirmed the validity of SRS for homogeneous models. However when scattering and absorption were heterogeneous both the TOI range and the quantitative accuracy decreased. Modelling scatter to be homogeneous showed range and accuracy improvements indicating inadequacies in the current SRS model concerning scattering assumptions.

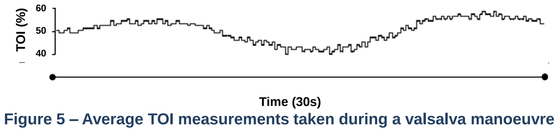

Figure 5 – Average TOI measurements taken during a valsalva manoeuvre [3].

In vivo data collected using the Niro-200NX (Hamamatsu) during valsalva manoeuvres confirmed the validity of the simulation findings for a fully heterogeneous mesh. A valsalva causes intracranial pressure changes of ~30% with similar changes expected in the TOI [4]. However the average brain TOI (***Fig. 5***) only changed by ~10%. The quantitative accuracy of the TOI is also lower than expected at ~50%, with baseline oxygen saturation in the brain expected to be ~75%.

The simulated data highlights limitations of the current SRS algorithm and suggests that a more complex model, incorporating heterogeneous scatter and regional reconstruction, is required to improve the validity of SRS.

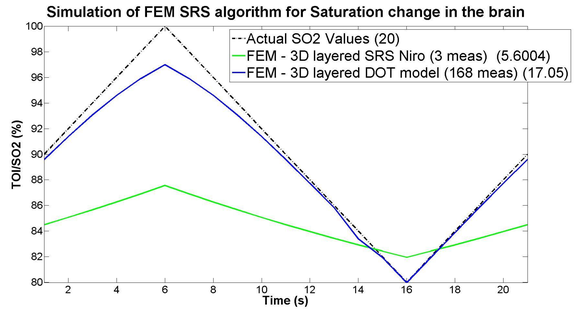

Figure 6 – Calculated TOI values for FEM SRS method using both DOT and Niro probe geometries.

To achieve this the SRS method was adapted to work with an FEM iterative reconstruction process where scatter and regions can be given as prior information. (***Fig. 6***) Performing FEM SRS using the Niro geometry yields 3 measurements of ∂A/∂ρ which was only sufficient to provide a global value of TOI. Albeit better than the original SRS in terms of quantitative accuracy, the range was still lower than expected.

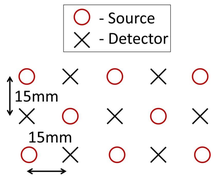

Figure 7 – Design for small scale DOT probe to improve FEM SRS results.

Table 3 – DOT probe specification

Wavelengths (nm)	Measurement pairs
735, 805 & 850	168

To obtain spatially and quantitatively accurate TOI values more overlapping measurements were required. Thus the move to a diffuse optical tomography (DOT) style probe shown in ***Fig. 7*** was made. ***Fig. 6*** shows that when the new DOT probe was used in conjunction with FEM tomographic reconstruction both range and quantitative accuracy were far superior to the original model and also to the Niro FEM SRS.

Conclusion

SRS provides increased sensitivity to changes in brain haemodynamics compared to standard NIRS measurements. Current TOI calculations are capable of identifying changes in brain saturation however the range and quantitative accuracy of the values are still susceptible to influences from superficial layers and heterogeneous scatter. Adaptation of SRS to work with a FEM reconstruction showed substantial improvements in quantitative accuracy of TOI. However FEM tomographic reconstruction methods provided the best overall TOI range and quantitative accuracy; this was due to 168 overlapping measurements from the DOT style probe (***Fig. 7***).

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