Title of session/talk: Advanced Neuroimaging 1/Functional MR Imaging of the Spinal Cord

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HIGHLIGHTS

- fMRI is possible in the spinal cord, but requires adaptation of brain fMRI methods
- Challenges include poor magnetic field homogeneity, and proximity to moving tissues/fluids
- Overcoming these challenges enables study of complete systems, and effects of injury or disease

TARGET AUDIENCE: This information will benefit researchers studying neuronal processes in the healthy or damaged spinal cord, and systems that are distributed across the CNS, such as pain.

OUTCOME: The challenges encountered with fMRI of the human spinal cord are identified, and methods that appear to be optimal to overcome these challenges, are demonstrated.

PURPOSE: The spinal cord and brainstem play critical roles in sensory and motor processing, and in pain, and can influence emotions and cognitive processing as well. Extending fMRI into the spinal cord has the potential to yield valuable new information that is otherwise inaccessible in humans.

METHODS

Identify the challenges: MRI of the spinal cord presents challenges of poor image quality due to poor magnetic field homogeneity and motion artifacts arising from the heart, lungs, and throat.[1] Fast imaging methods required for fMRI, such as with echo-planar imaging (EPI), are particularly sensitive to this environment. The choice of imaging method influences the parameters needed to attain optimal neuronal-activity-related contrast for fMRI, and the dominant sources, and effects, of physiological noise.

Overcome the challenges: In order to achieve fast acquisition times while avoiding EPI methods, single-shot fast spin-echo imaging, with partial Fourier acquisition (HASTE) is proposed. This method enables images to be acquired in thin sagittal slices to provide full 3D coverage of the spinal cord with good spatial resolution and fidelity. The optimal contrast was determined in spinal cord fMRI studies, with data acquired over a range of echo times (TE). Physiological noise has been characterized by means of computer simulations of cerebrospinal fluid (CSF) flow on image data, and with "Null" fMRI studies (no stimulus applied) to characterize autocorrelations and signal variance, and determine the influence of artifact correction schemes, motion correction, temporal filtering, and acquisition variants including parallel imaging (GRAPPA) and a range of repetition times (TR).

RESULTS: The optimal fMRI contrast-to-noise ratio in the spinal cord with spin-echo acquisitions has been determined be at a TE of approximately 75 msec. This value corresponds with established BOLD theory as it matches the tissue T_2 value. Physiological noise in spinal cord fMRI data, with HASTE, is seen to be dominated by motion artifacts arising from CSF flow linked to the cardiac cycle. The use of parallel imaging enables shorter TR values to be used, enabling more data to be acquired in an fMRI time-series. Parallel imaging also reduces some signal variance, possibly due to the reduced span of the cardiac cycle during sampling, and reduced loss of spatial resolution due to sampling k-space across multiple echoes. Signal fluctuations recorded in the spinal cord in Null studies were observed to have auto-correlations which are relatively low, and that decrease with shorter TR (increased T1-weighting). General linear model (GLM) analyses of Null data with an arbitrary paradigm were used to determine the t-value distributions, and identify departures from the expected Student's t-distribution.

DISCUSSION: The results of the error analysis support the conclusion that the dominant source of physiological noise arises from CSF. Methods currently used in our lab provide fMRI data spanning the cervical spinal cord and brainstem, with 1.5 x 1.5 x 2 mm^3 resolution, spin-echo BOLD contrast, and relatively low physiological noise from a known source that can be modeled and reduced in post-processing. The requisite balance is achieved between speed, resolution, and sensitivity. The sensitivity of these methods is supported by fMRI studies of pain responses, and analyses of the residual errors.

CONCLUSIONS: The challenges of functional MRI of the human spinal cord appear to have been effectively overcome. Studies of pain processing demonstrate the value of this method, both for basic research and potential for future clinical applications to monitor the effects of injury and disease or monitor treatment outcomes.

REFERENCES: 1. Leitch JK, Figley CR, Stroman PW. Applying functional MRI to the spinal cord and brainstem. Magn Reson Imaging 2010;28(8):1225-1233.