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Evaluation of Spinal Cord Function Using Functional MR Imaging with Neurophysiological Stimuli

Presently, excellent anatomic definition of cord and nerve root anatomy in normal and pathologic conditions can be obtained by using imaging techniques such as CT and MR imaging. Diffusion MR imaging has also recently been used to visualize the orientation of the nerve fiber tracts in the cord and to provide some measure of neuronal viability. But how can true cord *function* be visualized? Positron emission tomography has previously been used, with limited success, to assess cord metabolism. Functional MR imaging has been used extensively to evaluate brain function, but there have been very few studies on cord function. In this issue of *AJNR*, Backes et al attempt to evaluate spinal cord function with echo-planar functional MR imaging by using median nerve stimulation and fist clenching.

Although this article describes only preliminary results, showing true cord activation is a challenging task because of the presence of multiple potential complex artifacts. One of the major challenges that is necessary to overcome is motion effects, in particular, the presence of pulsatile CSF and vascular flow. Other problems include subject motion, respiratory motion, increased resolution, difficulties in shimming, and variations in local field inhomogeneity due to changing lung volumes.

Artifactual signal changes that seem to arise from cord gray matter can be generated through partial volume averaging or spatial motion misregistration. These changes can easily be mistaken for true cord activation because they can vary with the stimulation paradigms via changes in heart rate or respiration. If the pixels near the edge of the cord include both cord parenchyma and superficial vessels or CSF, artifactual activation can be generated through partial volume averaging. Peak CSF velocities can be large enough to cause inflow of unsaturated CSF spins into sections, causing artifactual activation. Similarly, inflow of unsaturated blood spins can occur into sections.

Misregistration artifacts can also arise from task-related motion artifacts, unless sophisticated motion-correction algorithms are used. Long examination durations can increase the risk of subject motion, especially if the subject responds to nerve stimulation. Artifactual activation may worsen if blood flow and CSF pulsations are triggered or linked to fist-clenching effort, subject motion, or responses to nerve stimulation, occurring at each epoch of the paradigm. In these cases, obtaining repeat images without nerve stimulation, to be used as control images for comparison, may help.

Cervical spinal cord motion can also produce misregistration artifacts because it can occur in both the longitudinal and transverse directions and

can lead to cord displacements of approximately 1 mm. These motions can become more complex and more extensive in the setting of compressive and degenerative diseases. Although cardiac gating may help to decrease potential errors arising from spinal cord motion, there may be additional effects from respiration and exercise-related blood pressure changes. Hemodynamic effects resulting from Valsalva maneuver, breath-holding maneuvers, and blood pressure changes can also affect functional MR imaging signals, either through fluid flow and neuraxis motion or more directly through the blood oxygen level-dependent levels.

The resolution of the functional MR imaging technique may be especially important in the functional evaluation of the spinal cord, because a pixel dimension of 2 mm is large relative to a cord diameter of 6 to 9 mm. Using smaller pixel sizes may provide better resolution, but this can increase misregistration artifacts. Larger pixel sizes would lower the misregistration effects relatively but can lead to greater partial volume averaging problems, especially near the surface of the cord. All these problems can become more significant in pathologic conditions in which the cord is narrowed or deformed.

Fist clenching or nerve stimulation synchronization of the functional MR imaging acquisitions with cardiac gating can increase the accuracy of the functional MR images. Additionally, performing additional control protocols with different stimuli may help to increase accuracy. For example, acquiring protocols with no fist clenching, or with no median nerve stimulation during the active periods, or with stimulation of an unrelated nerve may be useful as control tests.

Comparison of cord and brain functional MR imaging studies may not be entirely accurate. Functional MR imaging changes usually depend on a number of factors, such as blood oxygen level-dependent effect, blood volume, and perfusion. All these parameters may differ between brain and cord, and the coupling of neuronal activity and blood oxygen level-dependent effect may also differ. In cases involving pathologic abnormality of the cord, localization of functional cord areas relative to cord lesions such as tumors could become available, as with functional MR imaging of the brain. Intraoperative monitoring of cord function, sometimes performed to prevent neurologic injury while using techniques such as electromyography, presently provides some degree of information regarding cord function. With further developments, intraoperative functional MR imaging and MR imaging could provide continuous intraoperative monitoring of both spinal cord function and anat-

omy. In cases of spinal cord trauma or injury, additional pathophysiological information regarding cord function could also be obtained, and changes due to evolution of disease, response to therapy, and spinal cord plasticity could be evaluated.

Future developments of spinal cord functional MR imaging should include improvements in acquisition speed, physiological gating, motion correction algorithms, and susceptibility effects. In addition, the continued development of stimulation paradigms will be necessary and may include stimulation of other nerve tracts or the use of other stimulation techniques such as transcranial magnetic stimulation.

Finally, the presently available functional MR activation images indicate only the presence of neuronal activity but not whether the activity is the result of excitation or inhibition within a particular

region of the cord. This additional level of physiological information could be useful for the analysis of neural mechanisms and for the evaluation of neurologic diseases and of medical therapy and could be studied by novel forms of spectroscopy or by the use of appropriate pharmacophysiological interventions planned with the functional MR imaging studies.

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