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Review

The current state-of-the-art of spinal cord imaging: Methods

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ABSTRACT

A first-ever spinal cord imaging meeting was sponsored by the International Spinal Research Trust and the Wings for Life Foundation with the aim of identifying the current state-of-the-art of spinal cord imaging, the current greatest challenges, and greatest needs for future development. This meeting was attended by a small group of invited experts spanning all aspects of spinal cord imaging from basic research to clinical practice. The greatest current challenges for spinal cord imaging were identified as arising from the imaging environment itself; difficult imaging environment created by the bone surrounding the spinal canal, physiological motion of the cord and adjacent tissues, and small cross-sectional dimensions of the spinal cord, exacerbated by metallic implants often present in injured patients. Challenges were also identified as a result of a lack of "critical mass" of researchers taking on the development of spinal cord imaging, affecting both the rate of progress in the field, and the demand for equipment and software to manufacturers to produce the necessary tools. Here we define the current state-of-the-art of spinal cord imaging, discuss the underlying theory and challenges, and present the evidence for the current and potential power of these methods. In two review papers (part I and part II), we propose that the challenges can be overcome with advances in methods, improving availability and effectiveness of methods, and linking existing researchers to create the necessary scientific and clinical network to advance the rate of progress and impact of the research.

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Introduction

Non-invasive investigation of human spinal cord function, and the effects of spinal cord injury or disease, is significantly hampered by the inaccessibility of the spinal cord. In order to supplement current methods for assessing residual function, pain, and quality of life factors after spinal cord injury or disease, sensitive methods are needed to reveal changes in neurological function, and structure. Non-invasive imaging methods such as magnetic resonance imaging (MRI), positron emission tomography (PET), and computed tomography (CT), provide the only means of accessing the structure and function of the human spinal cord. As a result, there is currently a great need for development of these methods. While progress is being made, only a relatively small number of research labs in the world are actively working on spinal cord imaging methods, and these techniques have yet to be advanced into clinical use. The potential outcomes of advancing these methods are tremendous, enhancing our basic understanding of healthy human spinal cord function, and impacting our ability to accurately diagnose and treat injury and disease, and predict outcomes. In order to support the development of spinal cord imaging methods and advance the current technology, the objectives of this paper are:

1) to describe the current state-of-the-art of spinal cord imaging by reviewing current methodologies, and
2) to identify the current greatest challenges both innate to spinal cord imaging, and relative to hardware and software development.

This is the first of two papers, and is focussed on spinal cord imaging methods. X-ray based imaging methods such as plain film X-ray and CT demonstrate highly detailed images with contrast between soft tissues and boney structures and are already in routine clinical use for visualizing gross structural changes after trauma to the spine, and diseases of the intervertebral discs. Therefore only PET and MRI methods are described in this paper, with most of the attention on functional MRI (fMRI), diffusion-weighted imaging (DWI) and its extension to diffusion-tensor imaging (DTI), MR imaging based on magnetization transfer and identifying myelin water, and also MR spectroscopy. In a second paper, we will describe the current applications of these spinal cord imaging methods for assessing spinal cord injury, multiple-sclerosis, and pain. The overall goal of this work is to improve tools for spinal cord research and clinical assessments by overcoming the current challenges for imaging and make full use of the potential of these non-invasive methods.

Background

The anatomy of the spinal cord and surrounding structures renders the cord inaccessible for human research, and non-invasive imaging methods are therefore essential. It is also this anatomical arrangement that creates most of the challenges of imaging the spinal cord.

The spinal cord lies within the spinal canal inside the spine, and is surrounded by a variable layer of cerebrospinal fluid (CSF), and then a thick layer of bone or cartilaginous discs between the vertebral bodies. At its widest point of the cervical enlargement it is only ~15 mm across, and has an average length of approximately 45 cm in adult humans (Goto and Otsuka, 1997). The cerebrospinal fluid flows back and forth in the head–foot direction with each heart-beat, with a peak flow speak of roughly 3 cm/s, and with a general progression of movement down one side of the spinal cord and up the other (Feinberg and Mark, 1987; Matsuzaki et al., 1996). The pulsating CSF flow, and possibly arterial pulsation as well, cause the spinal cord to move within the spinal canal, with an amplitude that diminishes with greater distance from the head (Figley and Stroman, 2006, 2007). Given that the spinal cord ends at around the 12th thoracic vertebra (the exact location varies between individuals), the entire cord is relatively close to the heart and lungs.

The anatomical arrangement of the spinal cord is reversed from that of the brain, with the gray matter (largely nerve cell bodies, glial cells, and interneurons) within a characteristic butterfly-shape cross-section at the center of the cord, surrounded by white matter tracts. The main arteries supplying the cord lie along the cord surface, one above the anterior median fissure and two along the posterior side of the cord, and these are connected by lateral branches (Thron, 1988). The anterior artery sends branches into the anterior median fissure with further branching to supply the gray matter from the center outward. Venules and small veins carry blood radially from the gray matter to the cord surface.

MR methods, challenges and strengths

Imaging of the spinal cord presents inherent challenges that are common to all MR imaging and spectroscopy applications. Specifically, these are 1) the spatially non-uniform (inhomogeneous) magnetic field environment when in an MRI system, 2) the small physical dimensions of the cord cross-section, and 3) physiological motion. For non-MRI applications, such as PET and SPECT, the latter two of these challenges also apply. Here we discuss these key challenges for spinal