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Measurement of Vibration-Induced Volumetric Strain in the Human Lung

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Noninvasive image-based measurement of intrinsic tissue pressure is of great interest in the diagnosis and characterization of diseases. Therefore, we propose to exploit the capability of phase-contrast MRI to measure three-dimensional vector fields of tissue motion for deriving volumetric strain induced by external vibration. Volumetric strain as given by the divergence of mechanical displacement fields is related to tissue compressibility and is thus sensitive to the state of tissue pressure. This principle is demonstrated by the measurement of three-dimensional vector fields of 50-Hz oscillations in a compressible agarose phantom and in the lungs of nine healthy volunteers. In the phantom, the magnitude of the oscillating divergence increased by about 400% with 4.8 bar excess air pressure, corresponding to an effective-medium compression modulus of 230 MPa. In lungs, the averaged divergence magnitude increased in all volunteers (*N* = 9) between 7 and 78% from expiration to inspiration. Measuring volumetric strain by MRI provides a compression-sensitive parameter of tissue mechanics, which varies with the respiratory state in the lungs. In future clinical applications for diagnosis and characterization of lung emphysema, fibrosis, or cancer, divergence-sensitive MRI may serve as a noninvasive marker sensitive to disease-related alterations of regional elastic recoil pressure in the lungs. Magn Reson Med 000:000–000, 2012. © 2012 Wiley Periodicals, Inc.

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Magnetic resonance imaging (MRI) not only provides morphological images from within the human body but is also sensitive to a wide array of aspects of structural and functional states of living tissue. In particular, methods such as diffusion-weighted imaging, functional MRI, susceptibility-weighted imaging, MR angiography, perfusion, and strain and flow imaging (1) as well as MR elastography (MRE) (2) have important applications in clinical research and diagnostic radiology. The latter methods, particularly flow-sensitive MRI and MRE, are based on the acquisition of coherent motion fields (2,3). The motion itself is either intrinsically activated, e.g., through cardiac motion (4,5), blood flow (6), or respiration, or it can be externally induced through vibration generators attached to the body surface. In either case, information about motion fields is derived from acquisitions of three Cartesian motion components according to the vector nature of flow and oscillation fields. Striking applications are cardiac flow assessment (7), myocardial strain mapping (8), and elasticity-based staging of hepatic fibrosis (9). In contrast to flow-sensitive MRI, which quantifies the velocity of blood within vessels, MRE maps the distribution of the complex shear modulus given in units of kilopascals. Fast-imaging techniques allow for multislice data acquisition, as required for three-dimensional (3D) vector field MRI, with measurement times that are feasible for clinical application.

This article is about how motion field divergence in MRI can be exploited as a measure of the compression of a tissue of interest. Divergence is a strain invariant that depicts local volume changes caused by either intrinsic compression (or dilatation) or externally applied compression waves. It is important to note that biological soft tissue is not incompressible, as has been pointed out by Leiderman et al. (10), Konofagou et al. (11), and Righetti et al. (12) (with the background of ultrasound elastography under quasi-static conditions) and recently by Perriñez et al. (13–15) using dynamic MRE. The theoretical framework of regarding soft biological tissue as a compressible medium was developed within the theory of poroelasticity, which, in general terms, models a medium as a conglomerate of several compartments (16). Even if all compartments are incompressible, their interaction under stress can still lead to a change in volume, for example, as a consequence of fluid being squeezed out of the system. Other tissues, such as lungs, display compressibility due to their air-filled cavities. Regardless of the underlying model or type of tissue, the divergence operator translates deformation fields to compression maps that are most generally related to the inherent compression (bulk) modulus of the tissue. In this article, the divergence operator approach to MRI-measured motion fields for calculating volumetric strain (henceforth referred to as divMRI) will be outlined and studied in a phantom that includes air-filled cavities as well as in in vivo lungs of nine healthy volunteers. Our study is intended to introduce a new imaging parameter related to the compression modulus of tissue, which may provide important diagnostic information about pathological alterations of lung mechanical properties, as caused by emphysema, lung fibrosis, COPD, or lung cancer.

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