

# In Vivo Measurement of Volumetric Strain in the Human Brain Induced by Arterial Pulsation and Harmonic Waves

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**Motion-sensitive phase contrast magnetic resonance imaging and magnetic resonance elastography are applied for the measurement of volumetric strain and tissue compressibility in human brain. Volumetric strain calculated by the divergence operator using a biphasic effective-medium model is related to dilatation and compression of fluid spaces during harmonic stimulation of the head or during intracranial passage of the arterial pulse wave. In six volunteers, phase contrast magnetic resonance imaging showed that the central cerebrum expands at arterial pulse wave to strain values of  $(2.8 \pm 1.9) \cdot 10^{-4}$ . The evolution of volumetric strain agrees well with the magnitude of the harmonic divergence measured in eight volunteers by magnetic resonance elastography using external activation of 25 Hz vibration frequency. Intracranial volumetric strain was proven sensitive to venous pressure altered by abdominal muscle contraction. In eight volunteers, an increase in volumetric strain due to abdominal muscle contraction of approximately 45% was observed ( $P = 0.0001$ ). The corresponding compression modulus in the range of 9.5–13.5 kPa demonstrated that the compressibility of brain tissue at 25 Hz stimulation is much higher than that of water. This pilot study provides the background for compression-sensitive magnetic resonance imaging with or without external head stimulation. Volumetric strain may be sensitive to fluid flow abnormalities or pressure imbalances between vasculature and parenchyma as seen in hydrocephalus. Magn Reson Med 000:000–000, 2012. © 2012 Wiley Periodicals, Inc.**

**Key words:** cerebral pulsation; flow field; harmonic motion field; compression waves; shear waves; magnetic resonance elastography; poroelastography; porosity; brain tissue; venous pressure

## INTRODUCTION

Fluid pulsation is vital to brain function. On average, the brain receives 14% of cardiac output to sustain cerebral metabolism (1). Further supply of nutrients and waste

drainage are accomplished by cerebrospinal fluid (CSF), which additionally provides buoyancy and protects the brain from striking the cranium (2). The total volume enclosed by the rigid cranium is constant, leading to a tight interaction between blood volume, CSF volume, and intracranial pressure parameters such as hydrostatic parenchyma pressure, arterial pulsation pressure, venous pressure, and CSF pressure (3–5). Any imbalance in the mechanical coupling between arterial and venous blood pressure, CSF, and brain tissue impairs cerebral health and can lead to the development of disorders such as normal pressure hydrocephalus (6,7).

Since the advent of clinical magnetic resonance imaging (MRI), cerebral fluid flow and parenchymal displacement induced by cardiac pulsation have been studied extensively (4,8–13). In essence, there is consensus that the brain moves craniocaudally shortly after arrival of the arterial pulse wave (APW), accompanied by movement in the mediolateral direction (4) (Fig. 1). Despite the success of MRI in unraveling intrinsic brain motion, there is a paucity of data related to volumetric strain inside the cranium. Volumetric strain, which can be calculated by applying the divergence operator to motion fields, signifies local dilatation (positive strain) or local compression (negative strain). Since the divergence of motion fields is independent of the choice of coordinate axes, it represents intrinsic mechanical properties related to compressibility of tissue or to the compression modulus (14). Compressibility of soft biological tissue can be understood within the theoretical framework of poroelasticity (15), which has been applied to the brain mainly in the context of hydrocephalus (16–19). Poroelasticity accounts for fluid motion in a sponge-like material such that volumetric changes of the effective medium are related to the inflow and outflow of pore fluids. In this model, the compressibility of soft tissue is governed by its fluid permeability—a property which depends on the considered dynamic range (20). As a consequence of Biot's theory, harmonic stimulation causes three distinct wave modes, one shear wave and two compression waves each of which possessing distinct frequency-dependent attenuation properties. In this study, we will analyze cerebral volumetric strain due to the slow compression wave which is related to an inversely phased matrix-fluid motion (in contrast to in-phase motion of the fast compression wave known from ultrasound). Since the damping properties of this slow wave depends on the hydraulic conductivity of the brain, we expect to observe significant volumetric strain especially in the low dynamic range of elastography ( $< 70$  Hz), where

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