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Measurement of *in vivo* cerebral volumetric strain induced by the Valsalva maneuver

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ABSTRACT

Compressibility of biological tissues such as brain parenchyma is related to its poroelastic nature characterized by the geometry and pressure of vasculature and interconnected fluid-filled spaces. Thus, cerebral volumetric strain may be sensitive to intracranial pressure which can be altered under physiological conditions. So far volumetric strain has attained little attention in studies of the mechanical behavior of the brain.

This paper reports a study of measuring the in vivo cerebral volumetric strain induced by the Valsalva maneuver (VM) where forced expiration against a closed glottis leads to a transient increase in the intracranial pressure. For this purpose we applied three-dimensional magnetic resonance imaging equipped with a patient-controlled acquisition system to five healthy volunteers. With each volunteer, three experiments were performed: one with VM and two in resting state. i.e. normal ventilation, which were conducted before and after VM. The VM data were registered to reference data by morphology based non-rigid deformation, yielding 3D maps of total displacements and volumetric strain. On average, VM induced volumetric strain correlated to whole-brain dilatation of $-3.14 \pm 0.87\%$ and $-2.80 \pm 0.71\%$ compared to the reference states before and after VM, respectively. These values were well reproduced by repetitive experiments during the same scan as well as by repeated measurements in one volunteer on different days. Combined with literature data of intracranial pressure changes, our volumetric strain values can be used to elucidate the static compression modulus of the in vivo human brain. These results add knowledge to the understanding of the brain's biomechanical properties under physiological conditions.

1. Introduction

Brain mechanical properties are the subject of investigations in many disciplines of neurological research ranging from traumatic brain injury to inflammation and stroke (Bayly et al., 2012; Cheng et al., 2008; Di Ieva et al., 2010; Sack et al., 2013). Brain mechanical properties include a variety of constitutive parameters depending on the complexity of the underlying model. Complexity can be added to the simple isotropic elasticity model by accounting for energy loss, anisotropy, nonlinearity and poroelastic properties in order to improve predicted response of the brain to mechanical stimulations (Miga et al., 2000; Bilston et al., 2001; Miller, 2005; Kaster et al., 2011). However, even by measuring the brain's mechanical properties based on an isotropic elasticity model, which involves a shear and a compression modulus only, these constants must be considered as effective medium properties of a multiphasic hierarchically ordered material (Leiderman et al., 2006; Sack et al., 2013). The shear modulus is sensitive to the multiscalar geometry of biological tissues, giving rise to its pronounced dependency on the examined dynamic range while the compression modulus is related to the effective tissue pressure originating from fluid pressure in the vasculature and pores (Tully and Ventikos, 2009; Posnansky et al., 2012).

While in the last few years, magnetic resonance elastography (MRE) (Muthupillai and Ehman, 1996) has been utilized to study the shear modulus of the *in vivo* brain under healthy and pathological conditions, the cerebral compression properties remain elusive (Sack et al., 2008; Green et al., 2008; Kruse et al., 2008; Johnson et al., 2013; Clayton et al., 2011; Wuerfel et al., 2010). Recent developments in poroelasticity-MRE and volumetric

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