Stationary Super-Resolution Multi-Frequency Magnetic Resonance Elastography (SSR-MMRE) of the Human Brain

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Purpose

Increased image resolution at a given field strength is a widely sought after goal in MRI. Super-resolution techniques in which multiple lower-resolution images are combined to produce a higher-resolution image are widely used in the biomedical sciences, particularly microscopy, but until now had not been applied in combination with Magnetic Resonance Elastography (MRE) [1]. MRE, first described 20 years ago, vibrates tissue harmonically and encodes corresponding phase changes using motion-sensitised gradients. The resulting wave images are inverted to create maps of tissue elasticity and viscosity. Multi-frequency MRE (MMRE) fuses acquisitions at several actuation frequencies to enhance resolution and measure frequency-related dispersion. The multiple acquisitions in MMRE make it a candidate for application of Stationary Super-Resolution (SSR) in which multiple low-resolution images of the same scene are interpolated and fused to create a single, higher-resolution image, first described in [2].

In the present study the SSR technique was combined with Multi-Frequency Dual Elastovisco Inversion (MDEV), which solves for two viscoelastic parameters, the magnitude $|G^*|$ and the phase angle φ of the complex shear modulus G^*, by fusing complex-valued displacement fields from multiple acquisitions [3]. By SSR, images are interpolated prior to the image fusion in order to arrive at a higher resolution in the compound image. The technique was first validated on numerical simulations, to demonstrate recovery of subvoxel features in simulated data. The technique was then applied in a pilot brain study, comparing the impact of SSR on MDEV images obtained for a healthy subject, a patient with glioblastoma (GBM) and a patient with a brain metastasis (Met). Results were evaluated by correlating elastogram features with anatomical features as seen on the T2 image.

Subjects and Methods

Numerical Simulations: Finite-difference simulations were computed for a viscoelastic SH-wave PDE scheme using Java [4]. Simulated viscoelastic wave images were obtained at 20, 25, 30, 35, and 40 Hz with background stiffness of 3KPa, target stiffness of 12 KPa, and viscosity of 0.1 Pa s. Two targets were created: one large (12mm), which would be detected even after 1/4 downsampling, and one small (3mm) which would be below the resolution of the downsampling. The images were then downsampled to 1/4 of original size (8mm voxels). Four elastograms were obtained: original resolution, downsampled, upsampling without SSR (to control for the impact of interpolation alone), and upsampling with SSR.

In-vivo MRE Acquisition: Full wave fields in 15 axial slices were acquired using an EPI MRE sequence at seven frequencies [30:5:60 Hz] for the brain of three subjects: a healthy volunteer, a patient with glioblastoma (GBM) and a patient with metastasis (Met). The wave fields were Hodge decomposed using divergence-free wavelets [5] and denoised using complex dual-tree wavelets [6] with overlapping group sparsity (OGS) thresholding [7]. Wave images were then interpolated to 4 times the original resolution using a Lanczos-3 kernel and solved using MDEV for $|G^*|$ and ϕ.

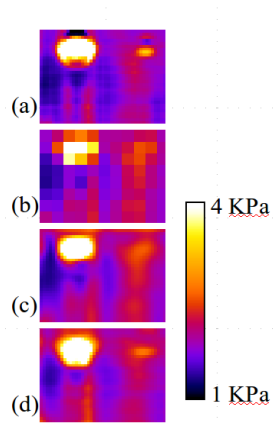
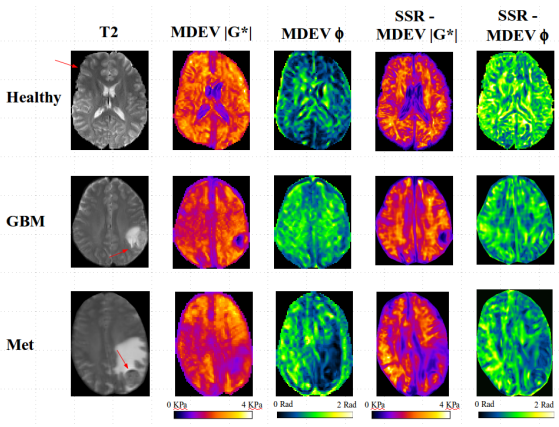
Results

Figure 1 shows numerical simulations: MDEV inversion ($|G^*|$) (a) at original high resolution, (b) MDEV down-sampled to low resolution (8mm voxels), (c) low-resolution MDEV up-sampled and (d) SSR-MDEV based on low-resolution wave images, interpolated prior to MDEV. The small inclusion is spatially resolved in (a) and in (d), while it cannot be distinguished from its background in (b) and (c).

In Figure 2 T2 anatomical features are compared with results for MDEV and SSR-MDEV. In the healthy brain, gray matter registers in both methods, however SSR contains specifically gray matter voxel values, and a well defined interface can be seen between CSF and the pial surface. In the glioblastoma and the metastases, both the MDEV and SSR-MDEV elastograms contain detail not seen in the standard T2-weighted MR image. The glioblastoma is found to contain a soft necrotic core and a stiffer, more viscous perifocal region, while the metastases contains a hard but low viscosity core with a soft perifocal region of glial cells. However, voxels for core and perifocal regions without partial volume effects are found in the SSR. Finally, the interface between the regions of gliosis and oedema in the metastases is well depicted in the SSR-MDEV $|G^*|$ image despite both areas having low stiffness.

Conclusion

SSR applied to MDEV-based MMRE enables spatially resolved recovery of sub-voxel features, resulting in a new level of radiological detail in both $|G^*|$ and ϕ, and enabling viscoelasticity measurements with reduced partial volume effects

Figure 1	Figure 2
	

Sources: [1] Muthupillai et al. Science 1995:5232:1854 [2] Elad et al. IEEE Trans Im Proc 1997:6(12):1646 [3] Papazoglou et al. Phys. Med. Biol. 2012:57:2329 [4] Virieux et al. Geophys. 1984:49(11):1933[5] Ong et al. MRM DOI:10.1002/mrm.25176 [6] Selesnick IEEE Sig Proc Mag 2005:22(6):123-151 [7] Chen et al. IEEE Trans Sig Proc 2014:62(13):3464-3478