Inversion Algorithms for MRE, MRE of Breast Cancer

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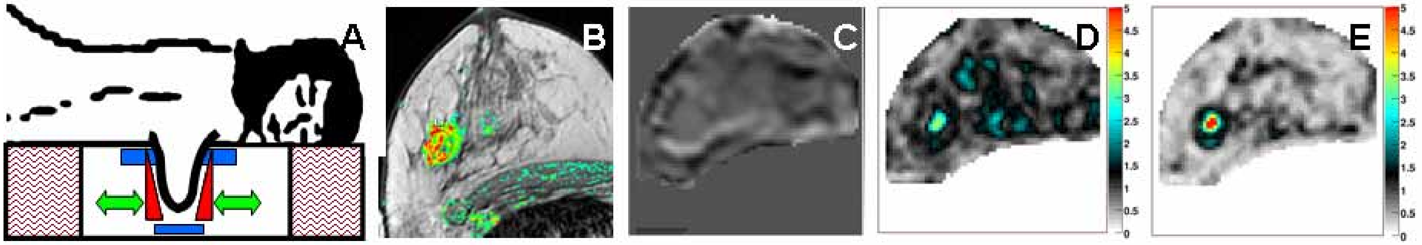
MR-elastography (MRE) represents a novel imaging modality which is capable to overcome the limitations of manual palpation [1]. Based on classical MR-imaging techniques, it allows imaging the propagation of low frequency acoustic waves within tissue. Since the local properties of the acoustic wave are tightly linked to the underlying viscoelastic properties of the medium, it is therefore possible to reconstruct locally the complex shear modulus G* of tissue [2]. Thereby, palpation has turned into the assessment of an objective absolute physical quantity, whose diagnostic value can be quantified.

Dynamic MRE, which typically operates monochromatically, yields in the linear regime the complex shear modulus $G^*=G_d+iG_l$ at one single frequency, which links the applied stress to the resulting strain. G* is deduced from the displacement measurements using the well-known equation of motion for mechanical waves in viscoelastic media. Reconstruction, i.e. the step from measured displacement data to calculated local viscoelastic properties, faces a severe problem: the presence of the compressional wave in the measured displacement field. Its contribution must not neglected for heterogeneous objects (even in case of pure shear excitation), but its consideration in the partial differential equation fails due to the almost incompressible nature of tissue [3]. The problem is characterized by the enormous difference in magnitude between the shear modulus (about kPa) and the second Lamé coefficient (about GPa) in soft tissue which is manifested by a huge difference in propagation speed among the compressional wave (~1550m/s) and the shear wave (~1-10m/s). It can be shown that the remaining compressibility of tissue, which is of very small magnitude, balances minutely the large magnitude of the second Lamé coefficient. This makes reconstruction impossible if no additional measures are taken. Apart from brute force low-pass filtering in the spatial frequency domain (for the removal of the long wavelength components of the compressional wave), there are two exact ways out of the deadlock: on the one hand the so-called Helmholtz-Hodge decomposition allows extraction of the transversal displacement component by solving an additional equation for an unknown vector potential; on the other hand it is possible to apply the curl-operator to the partial differential equation. It acts as a projection operator, because the compressional wave is curl-free. The drawback of the second technique is the involvement of third-order spatial derivatives, while the difficulty of the first method is it sensitivity to boundary conditions. Either way, both methods enable the removal of the compressional wave and lead to a Helmholtz-type equation with only the shear-viscoelastic parameters as the unknown coefficients (assuming isotropy). Here, ultrasound based elastography techniques [4] have an advantage since they are capable to operate in the time-domain due to their real-time capabilities. Thereby, the shear and compressional components separate in time due to their large difference in propagation speed.

Breast cancer often shows a desmoplastic stroma reaction in terms of a reactive proliferation of connective tissue so that a dense layer of fibroblasts accumulates around malignant breast epithelial cells. This leads to a hardening of the breast tissue which can be diagnosed by palpation. The diagnostic importance of palpation within the domain of breast cancer diagnosis is undisputed in terms of breast self examination as well as clinical breast examination [5]. However, this method lacks precision and objectivity because it relies on individual perception and skill. Moreover sensitivity is low especially in case of small tumors. Thus, MRE as an objective technique for the assessment of mechanical properties of lesions is expected to provide useful diagnostic information. Currently, MR-mammography (MRM) is performed in combination with the administration of contrast agent. Here, one follows the temporal change of the MR-signal intensity within the lesion after intravenous application of a contrast medium bolus (typically gadopentetate dimeglumine). Dynamic MRM has demonstrated such an enormous sensitivity that a non-enhancing invasive malignant lesion merited initially a case report. Thus, when applying MRE to the breast it is mandatory to combine it with the already established technique of MRM. Typically the patient is in prone position with the breasts gently attached to a mechanical transducer (A). Fig.B shows the contrast enhanced T1-weighted gradient echo image of the right breast in transverse orientation of an invasive ductal carcinoma with the corresponding maximum signal enhancement after bolus injection overlaid in color. The image of the mechanical waves as measured via a motion sensitized MR-sequence is presented in C. As clearly visible, the local wavelength of the shear wave increases at the location of the lesion. Reconstruction provides the images of G_d (D) and G_l (E) indicating that the viscoelastic properties of the lesion are strongly altered when compared to the surrounding background tissue. Recently, our group conducted a study to explore the potential diagnostic gain provided by the viscoelastic shear properties of breast lesions for the improvement of the specificity of contrast enhanced dynamic MR-mammography [6]. The combination of the BIRADS categorization obtained via MR-mammography with viscoelastic information lead to a substantial rise in specificity. Analysis of 39 malignant and 29 benign lesions showed a significant diagnostic gain with an increase of about 20% in specificity at 100% sensitivity.



A: Experimental setup combining MRM and MRE with the patient in prone position. B: T1-weighted gradient echo image of the right breast in transverse orientation with the corresponding maximum signal enhancement after bolus injection overlaid in color. C: Snap-shot of propagating shear waves in steady state within the breast. Real-part (D) and imaginary-part (E) of the complex shear modulus after post-processing the shear wave data. The lesion is characterized by a significant increase in Gd (i.e. it appears stiffer) and an increase in Gl (i.e. it appears more viscous).

References

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