Determination of Non-linear Elasticities using dynamic MR Elastography

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Synopsis

Elastic properties of tissues can be quantitatively determined observing shear wave patterns in MRI. The evaluation of local wavelengths yields linear elastic material constants. However, many *in vivo* tissues show strong deviations from linear elastic behavior. Here, a technique is introduced based on MR elastography that allows to measure non-linear elastic properties by analyzing the frequency-content of shear vibrations. The method allows a spatially and temporally resolved observation of the propagating shear waves. Experiments were performed on Agarose exposed to 150Hz harmonic shear vibrations. Selective filtering of the 4^{th} and 5^{th} harmonics resulted in signals, which could be attributed to non-linear elastic properties using a numerical solution of Burger's equation.

Introduction

Non-linear elasticity is a sensitive mean to characterize the mechanical properties of tissues [1,2]. Even isotropic materials with identical shear modulus (μ) can exhibit differences in their non-linear stress-strain behavior due to small variations on a molecular level [3,4]. Those subtle elastic differences can be explored using dynamic MR Elastography (MRE) [5]. The method relays on a magnetic encoding of tissue displacements by oscillating gradients. Displacement of the material is imposed in terms of strain wave fields applied in an acoustic range of 50-500vHz with amplitudes up to 1 mm. Non-linear constitutive properties can generate "shock" waves with an anharmonic shape that depends on the underlying strain-energy function of the material [7].

Methods

Non-linear MRE Experiments were performed on Agarose using 150 Hz harmonic shear vibrations (f_v). The linear vibration-behavior of the excitation unit was ensured by motion tracking coils mounted on the actuator [6]. The applied non-linear MRE sequence allowed a spatial resolution in 1D combined with an incrementally progressing delay between excitation and motion encoding. Gradient frequency (f_G) was set to 600 and 750 Hz for detecting the 4^{th} and 5^{th} harmonic vibrations, respectively. The gradient period number (n_G) was kept variably for either choosing the filter condition ($n_G = f_G / f_v \cdot n$; n = 1,2,3...) or to allow an additional encoding of the fundamental frequency. FFT was applied to the experimental wave patterns along the time dimension to evaluate the signal intensities of distinct harmonic oscillations. The experimental data were reproduced by numerical simulations using a non-linear elastic modulus $E(F) = 3E_1F^2 + 2E_2F + \mu$ as elastic coefficient in Burger's equation. F was considered as deformation gradient that consists of both transversal and longitudinal deformation components due to the mechanical characteristics of the actuator.

Results

The experimental shear waves observed in Agarose were found to exhibit high harmonic content up to 750 Hz with 150 Hz forced vibration. The amplitudes of the 4^{th} (600 Hz) and 5^{th} (750 Hz) harmonic increased with an increasing distance to the actuator (see Fig. 1). There was no anharmonic component introduced by the actuator. From numerical calculations of the 600 and 750 Hz signal amplitudes non-linear elasticity coefficients of E_1 = 57 ± 3 kPa and E_2 = 4 ± 2 kPa were determined (see Fig. 2). The shock distance of the waves was measured with approximately 20 mm. Furthermore, the presence of even harmonic vibrations (600 Hz) revealed a small longitudinal deformation component of about 5%.

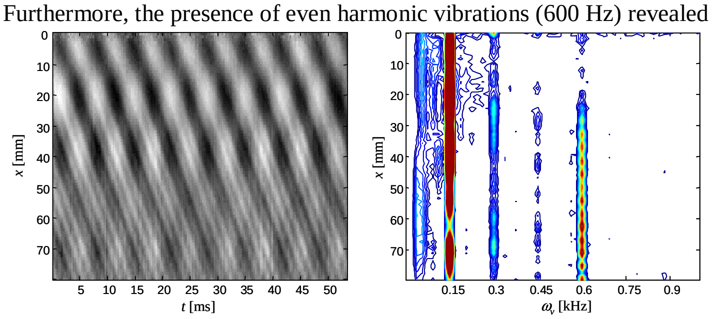

Fig. 1: Experimental *x-t*-wave image (left) and its 1D-Fourier transformed (right). The waves were recorded with f_G = 600 Hz and n_G = 19 causing the presence of the dominant excitation frequency , f_v = 150 Hz vibration.

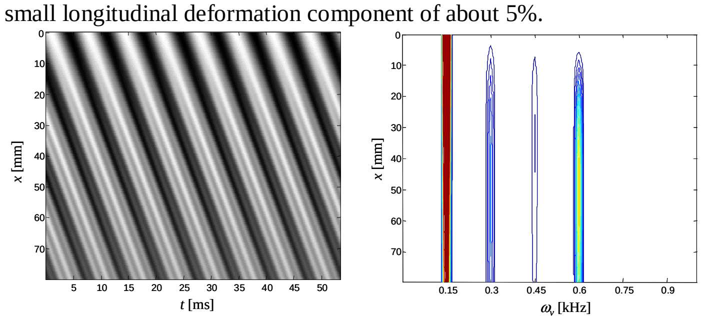

Fig. 2: Numerical simulations of the experimental case shown in Fig. 1. It is clearly visible that higher harmonic vibrations increase their amplitudes with the distance the wave is propagating. The slope of the non-linear intensities is a function of the non-linear parameters E_1, and E_2 as well as of the damping of the oscillations.

Conclusion

It has been shown that MR Elastography is capable of detecting non-linear elastic material properties by observing the harmonic content of shear waves. The experimentally observed amplitudes of the higher harmonic vibrations agree well to predictions of the theory of non-linear elasticity. These data demonstrate that non-linear MRE shows promise as a novel means to determine the elasticity of tissues beyond that characterized by the linear shear modulus.

References

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