Synchronisation of shear vibrations and balanced steady state free precession in MR Elastography (SSFP-MRE)

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Introduction MR elastography (MRE) allows the non-invasive measurement of in-vivo tissue elasticity which is gained from phase difference images [1]. The phase signal shows a linear increase with the integral of the bipolar motion encoding gradients (MEG) if vibration and gradient frequency match. However, the phase signal gain is compromised by the loss of transversal magnetization due to T_2 spin dephasing during encoding time. Corresponding to this loss the number of possible MEG cycles is limited, causing low signal-to-noise ratio (SNR) images in common MRE; in particular for tissues with short inherent T_2 time like muscle or liver [2, 3]. In the following, a new balanced steady-state free precision (SSFP) MRE experiment is described that combines MRE displacement encoding with acquisition of high SNR images in seconds. The experimental setup of mechanical vibration and motion encoding by SSFP-MRE is demonstrated on agar agar gel and ex-vivo bovine liver with special regard to the frequency selectivity to non-linear vibrations.

Methods A balanced SSFP sequence was enhanced by trapezoidal MEGs [4] with variable frequency (f_G) and cycle number (N_G) symmetrically positioned between slice selection- and readout-gradient as shown in fig. 1. For highest encoding efficiency the mechanical actuator was driven by a sinusoidal current with frequency $f_O = N_O / TR$ synchronized to the motion encoding gradient with N_O being the oscillation period number. MEG and synchronized vibration are related to each other with:

$$\frac{N_O}{f_O} = TR_{\min} + \frac{N_G}{f_G}$$

as demonstrated in fig. 2. $TR_{\min}$ is given for $N_G = 0$ and depends solely on MR hardware and physiologic constraints (e.g. stimulation, SAR). In the following, a MEG frequency $f_G = 3f_O$ and $N_G = 2$ was chosen to encode the 3rd harmonic of the excited fundamental vibration.

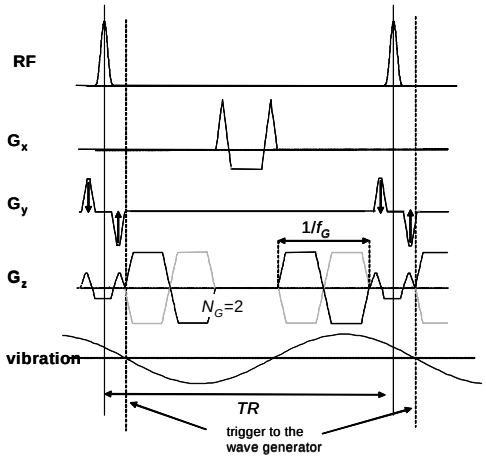

Fig. 1: SSFP-MRE sequence with trapezoidal motion encoding gradient (MEG) in slice (*z*) direction. Grey lines represent the SSFP-MRE sequence with inverted MEG polarity

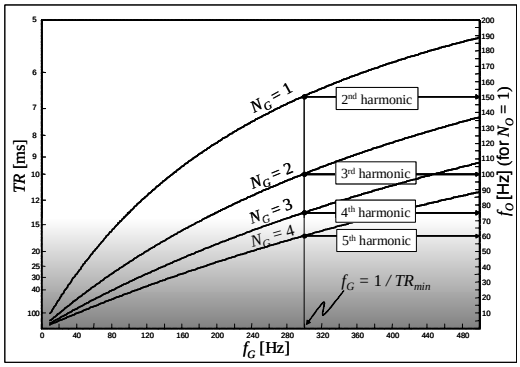

Fig. 2: *TR* and vibration frequency $f_O = 1/TR$ versus MEG frequency f_G for $TR_{\min} = 3.3$ ms. If f_G is chosen to be $1/TR_{\min}$ the highest encoding efficiency is achieved for the harmonic $N_H = f / f_O$ with $N_H = N_G + 1$ cycles (arrows). The bold curves show *TR* for any other MEG frequency with $N_G = 1..4$.

Results and Discussion In addition to the 3rd harmonic (fig. 3 c) the much stronger fundamental and 2nd harmonic vibration (fig. 3 a, b) were detected in a single experiment. Both materials create higher harmonic vibrations due to inherent non-linear elastic properties. This observation is supported by the fact that both 2nd and 3rd harmonic vibration amplitudes increase while the wave is traveling through the material according to the accumulation of inharmonic displacements [5]. This non-linear effect is pronounced in agar agar gel, where the wave amplitude of the 3rd harmonic vibration becomes visible after approximately 3-4 cm. In contrast, liver already shows the presence of higher harmonics directly beneath the actuator surface. Since the phase information in SSFP-MRE is not spoiled after each *TR*, the motion-encoded phase signal accumulates and the phase-to-noise ratio (PNR) is improved. Furthermore, symmetrically positioned MEGs maintain the advantages of balanced SSFP by using the concurrence of spin- and gradient-echo to full capacity. A careful choice of *TR*, MEG bandwidth and vibration frequency is required to achieve an optimal encoding efficiency but *TR* should be minimized to avoid banding artifacts. Nevertheless, efficient shimming is essential in SSFP-MRE.

Conclusion The shown SSFP-MRE experiments demonstrate the feasibility of the new technique to shorten MRE examinations with high SNR and PNR of balanced steady-state imaging and frequency selective motion encoding. The signal amplitude of weak higher harmonic vibrations is accessible while their fundamental frequency is simultaneously observed.

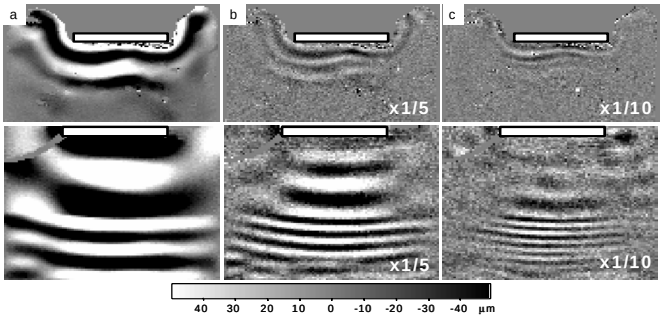

Fig. 3: Experimental SSFP -MRE wave images of ex-vivo bovine liver (upper row) and agarose (lower row) with $f = 1/TR$ (a), $2/TR$ (b) and $3/TR$ (c) ($f_G \approx 300$ Hz, $N_G = 2$, $f_O \approx 100$ Hz, $N_O = 1$), the position of the excitation plate is demarcated as a bar at the upper boundary of the objects.

References:

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