# Balanced Alternating Steady-State Elastography

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**Introduction.** Many pathologies in soft tissues, such as muscles, lymph nodes, liver and adipose tissue cause a change in the mechanical properties, and magnetic resonance elastography (MRE) offers a non-invasive diagnostic method that extends the physician's ability to assess tissue elasticity throughout a patient's body (1). We propose a new *balanced alternating steady-state elastography* (*BASEL*) MRE technique that makes use of the high sensitivity of the dynamic equilibrium state to alternating spin dephasing, as we have recently described in the analysis of residual eddy currents (2), to map elastographic contrast onto a single modified balanced steady state free precession (b-SSFP) experiment.

**Methods.** Figure 1 shows a possible BASEL sequence timing which generates alternating precession angles and thus alternating steady states in the presence of transverse acoustic strain waves. All three gradient axes are fully balanced over each TR interval, and alternating RF pulses for excitation are applied. Propagation of an acoustic strain waves of frequency ω results in a cyclic displacement $\Delta\mathbf{r}(n,t)$ with time $t$ ($t=n\cdot\mathrm{TR}+t_{\mathrm{TR}}$) of an isochromat, synchronized with TR such that the polarity alternates between odd and even TR intervals. The read gradient is designed to accumulate an alternating phase,

$$\Delta\mathbf{r}_\omega(n,t) \sim (-1)^n \cdot \sin(\omega t_{TR} + \mathbf{kr}) \;\;\Rightarrow\;\; \vartheta_{ext}(n,\mathbf{r}) \sim (-1)^n A \cdot \sin(\varphi + \varphi_0) = \gamma \int_{(n-1)\cdot TR}^{n\cdot TR} \left\langle \Delta\mathbf{r}_\omega(t) \middle| \mathbf{G}(t) \right\rangle dt$$

within each TR interval due to the alternating polarity of the mechanical motion, whereas phase and slice selection gradients are designed to be insensitive to the oscillatory motion. Precession angles $\vartheta_{ext}$ depend on phase $\varphi$ (and thus position **r** and wavenumber **k**, $\varphi$=**kr)**, have a time dependent phase shift $\varphi_0$ and are directly proportional to the amplitude $A$ of the mechanical excursion. As a consequence, an oscillating steady-state is produced that depends on the alternating, motion-induced phase offset $\vartheta_{ext}$ and on intrinsic off-resonance frequencies (Fig. 2a, from simulations: $T_1$=500ms, $T_2$=50ms, TR=6ms, $\alpha$=40°). A special case of oscillating steady-states in SSFP can be found in the work of Vasanawala et al (3).

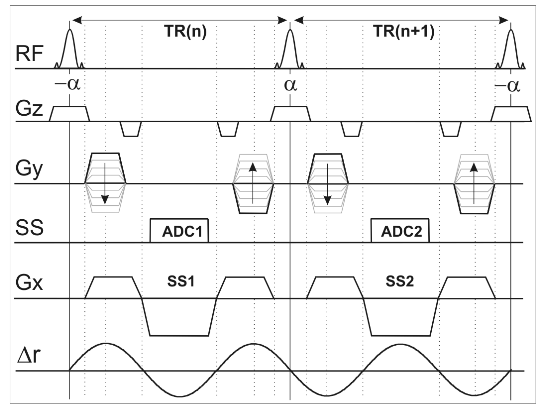


Fig.1.: *BASEL* sequence scheme.

**Results & Discussion.** Transverse acoustic strain waves at 250Hz were generated using a piezoelectric actuator coupled into a 1% agar-agar cylindrical phantom (18cm height and 12cm diameter) as described elsewhere (4). Off-resonance in deg/TR and displacement maps in microns are shown in Fig. 2b. Typical wave images of a transverse acoustic strain wave given by steady-state phase and amplitude modulation are shown in Fig. 2c. In contrast to the phase image (top), the wave pattern and reflection on the walls of the cylinder are clearly evident in the amplitude image (bottom) within the whole phantom. As expected (see simulations, Fig. 2a), amplitude images show a high sensitivity to alternating precession angles over a broad range of off-resonance frequencies. However, phase reversal in the mapped wave is clearly evident in the transition regions from negative to positive off-resonance frequencies (white arrow in the figure). A profile along the direction of propagation of the transverse wave shows harmonic oscillations in both steady state phase and amplitude images. Perturbations in steady-state are very effective even for displacements of a few microns (see Fig. 2b). Compared to standard MRE sequences, BASEL circumvents the disadvantages of repetitive magnetization preparation and thereby improves scan-time efficiency by at least one order in magnitude for comparable sensitivity.

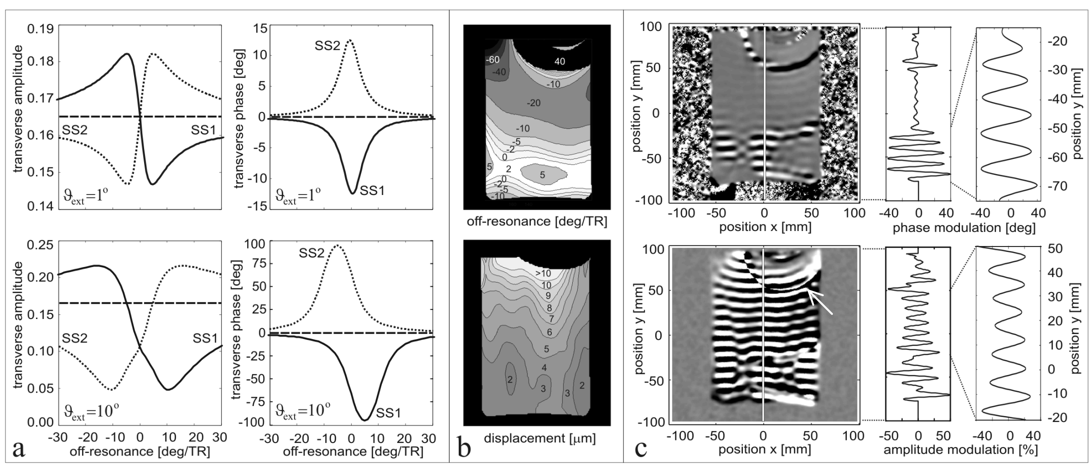


Fig. 2a: Simulation of steady-state amplitude and phase dependence on off-resonance frequencies for 1° (top) and 10° (bottom) alternating precession angle. Fig. 2b: Reference measurements. (top) Off-resonance map using phase information from a FLASH sequence at two different echo-times ($TE_1$=5ms, $TE_2$=10ms, TR=20ms and $\alpha$=15°). (bottom) Displacement maps calculated from standard MRE methods. Fig. 2c: BASEL MRE phase (top) and amplitude (bottom) images.

**Conclusion.** The method compares favorably with other methods for MRE imaging and can provide additional contrasts due to the availability of both amplitude and phase maps and combinations of images inferred from both steady states. Furthermore, contrast does not rely on the flip angle. Quantitative information about mechanical displacements, however, cannot be gained solely from steady-state amplitude and phase modulations, and additional information, such as relaxation times and distribution of off-resonances, is required. Finally it should be emphasized that the BASEL method can be applied to any modality that produces alternating phase perturbations, for example, generated by alternating currents applied to the sample, or external alternating electric fields that produce alternating motion of charged particles.

**References.** [**1**] Muthupillai R, *et al.*, Science 1995;269(5232):1854-1857. [**2**] Bieri O, Scheffler K. Proc ISMRM 2004;12:104.
[**3**] Vasanawala SS, *et al.*, MRM 1999;42(5):876-883. [**4**] Uffmann K, *et al.*, MR Engineering 2002;15(4):239-254.