MLS-Coded ARF Excitation for Noise-Resilient Shear Wave Elastography

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***Abstract*—This study proposes a shear wave elastography (SWE) technique based on maximal length sequence (MLS) coded acoustic radiation force (ARF) excitation combined with frequency-domain pulse compression. The goal is to enable robust SWE measurements under low-voltage conditions where conventional single-push (SP) methods suffer from low signal-to-noise ratio (SNR) due to safety constraints on acoustic output. A 127-bit MLS sequence was used to modulate the ARF push, distributing the energy over long ARF excitations while maintaining a low peak voltage. After compression, the induced displacement fields exhibited impulse-like profiles with enhanced SNR. In vivo measurements were performed on the human biceps brachii using three excitation modes: high-voltage SP (60 V), low-voltage SP (20 V), and low-voltage MLS-coded excitation (20 V). Under low-voltage conditions, MLS increased the SNR from –3.5 dB (SP) to 5.6 dB, recovered accurate group velocity estimates (5.26 m/s, $R^2 = 0.93$), and preserved stable phase velocity profiles up to 900 Hz. In contrast, low-voltage SP produced unreliable group velocity (–8.83 m/s, $R^2 = 0.15$) and degraded phase velocity at high frequencies. The results demonstrate that MLS-coded excitation enables high-quality SWE at reduced acoustic exposure, expanding its applicability to safety-sensitive tissues such as neonatal or lung.**

***Index Terms*—Shear wave elastography, Pulse Compression, ARF, MLS**

I. Introduction

Shear wave elastography (SWE) is an ultrasound-based imaging technique that enables noninvasive quantification of tissue stiffness by analyzing the propagation speed of mechanically induced shear waves. Over the past decade, SWE has demonstrated clinical relevance in diverse applications, including liver fibrosis staging, assessment of muscle mechanics, tumor characterization, and vascular diagnostics [1]. Among the various excitation strategies, acoustic radiation force (ARF)-based methods are the most widely adopted, as they rely on focused ultrasound bursts to remotely generate localized tissue displacements [2].

However, the effectiveness of ARF-induced SWE is strongly influenced by the amplitude of the resulting shear wave. In clinical practice, the acoustic energy that can be delivered is constrained by regulatory limits on the mechanical index (MI) and thermal safety, especially in tissues that are highly attenuating or sensitive to acoustic exposure [3]. These limitations pose challenges in regions such as the lung, neonatal brain, or peripheral vasculature, where the induced displacements are often weak and the signal-to-noise ratio (SNR) becomes insufficient for reliable wave tracking and elasticity estimation.

To address these constraints, alternative excitation schemes are needed that can increase the effective energy transferred into the tissue without raising the peak acoustic pressure. Coded excitation techniques—commonly employed in Doppler and B-mode imaging—offer a promising solution through the principle of pulse compression [4]. By spreading the energy over a longer coded waveform and subsequently compressing it in time, these methods enhance signal detectability while remaining within safety limits.

Despite their proven utility in conventional ultrasound imaging, pulse compression strategies have seen limited application in elastography, particularly for encoding ARF-induced shear waves [5]. In this work, we investigate the use of maximal length sequences (MLS)—a class of pseudorandom binary codes with ideal autocorrelation properties [6]—as a coding strategy for ARF excitation in SWE. The proposed method modulates the ARF waveform using a MLS sequence and reconstructs the tissue response via frequency-domain deconvolution to yield an impulse-like waveform with improved energy concentration.

This approach was implemented on a programmable ultrasound system and evaluated in vivo in the human biceps brachii muscle. Three excitation scenarios were tested: single-push (SP) at high voltage, SP at low voltage, and MLS-coded excitation at low voltage. The performance of each method was assessed using key elastographic metrics, including signal-to-noise ratio, group velocity, and frequency-dependent phase velocity. The results demonstrate the potential of MLS-coded excitation to enable robust SWE measurements in acoustically constrained or safety-sensitive environments.

II. Methods

A. MLS-coded ARF Excitation and Signal Processing

To enhance the displacement signal-to-noise ratio (SNR) in shear wave elastography (SWE), a coded excitation scheme based on a 127-bits maximal length sequence (MLS) was implemented for the acoustic radiation force push [7]. Each bit of the binary MLS sequence triggered a focused ultrasound

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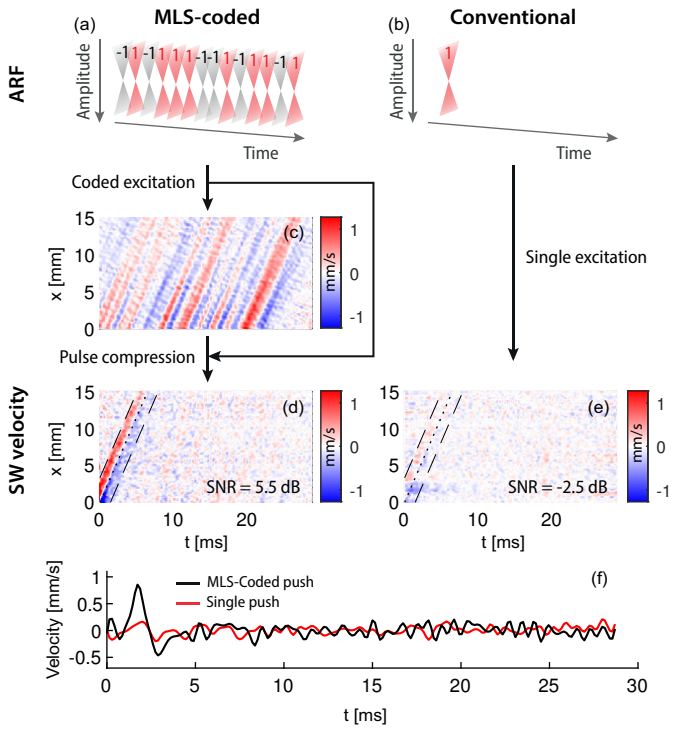


Fig. 1. Workflow of the MLS-based pulse compression method (a) in comparison to the conventional single push method (b). In the context of the MLS method, the initial step entails the encoding of shear wave signals by ARF (c), followed by the subsequent compression of these signals in the frequency domain through the implementation of pulse compression. A comparison is made between the propagation maps (x, t) of shear waves using the MLS method (d) and the single-push method (e) in 2D at the focal depth and 1D at lateral distance of 5 mm from the focal ARF point (f). The signal-to-noise ratio of which is quantified.

burst of 100 μs, followed by an inter-bit delay of 250 μs to ensure thermal safety and avoid transducer overheating. The total duration of the coded ARF sequence was approximately 45 ms.

All excitations were transmitted at 4.5 MHz using a 128-element linear array transducer (L11-4v, Verasonics Inc.) with an f-number of 2 and a focal depth of 15 mm. Shear wave propagation was tracked using high-frame-rate plane wave imaging at 7.24 MHz with a pulse repetition frequency of 10 kHz. Identical acquisition parameters were employed for both single-push (SP) and MLS-coded excitations to enable direct comparison.

The displacement response to the MLS-coded ARF was recovered via frequency-domain deconvolution between the measured shear wave field (Fig. 1.c) and the known input sequence (Fig. 1.a). This pulse compression process yielded an impulse-like displacement profile (Fig. 1.d), effectively concentrating the delivered energy without increasing the peak acoustic output. The corresponding SP response is shown in Fig. 1.b for comparison.

Particle velocity fields were estimated using one-dimensional autocorrelation of the in-phase and quadrature (IQ) components of the received RF data [8]. The raw displacement traces were then bandpass and directional filtered [9] to obtain high-resolution spatiotemporal maps of shear wave propagation.

B. In Vivo Acquisition and Propagation Analysis

To evaluate the performance of the proposed excitation scheme under realistic clinical conditions, an in vivo acquisition was performed on the biceps brachii muscle of a healthy volunteer (Fig. 2.a). B-mode ultrasound imaging was used to place the probe longitudinally with respect to the muscle fibers (Fig. 2.b). Shear waves were induced using three different excitation modes: (1) a conventional single-push with high input voltage (60 V) and high acquisition frame rate was used as a reference condition, (2) an SP with low input voltage (20 V), and (3) an MLS-coded ARF sequence also at 20 V. In all cases, the transmitted frequency, focus, and imaging parameters were kept constant.

Axial particle velocity fields were reconstructed from plane wave acquisitions and processed to obtain spatiotemporal propagation maps (x, t). From these maps, three key parameters were computed to assess the signal quality and reconstruction performance of each excitation mode.

First, the SNR was calculated by dividing the root mean square amplitude of the main shear wave at each lateral position by the standard deviation of the baseline noise in a post-push interval. The resulting SNR values were averaged over the lateral field of view. Figs. 2.d-e show an example of the areas selected as signal for SNR calculation which are marked with dashed lines.

Second, the group velocity (c_g) was estimated by tracking the time-of-flight of the shear wave peak along the lateral dimension. A linear regression was performed on the arrival times, and the slope of the fitted line was used to compute the average group velocity [11].

Third, phase velocity (c_{ph}) was estimated as a function of frequency by applying a two-dimensional Fourier transform to the (x, t) maps [10]. For each frequency component, the velocity corresponding to the maximum spectral amplitude was extracted, yielding a frequency-dependent phase velocity curve.

III. Results

The performance of the three ARF excitation strategies was evaluated in vivo by analyzing the shear wave fields generated in the biceps brachii muscle. Figure 2 summarizes the experimental results for each configuration: (a–c) show the spatiotemporal shear wave propagation maps; (d–f) display the corresponding particle velocity profiles; and (g–i) present the phase velocity spectra in the frequency–phase velocity domain.

The signal-to-noise ratio (SNR) was assessed for the two low-voltage excitation modes to evaluate their robustness under constrained acoustic conditions. In the conventional SP case, the average SNR was -3.5 dB, indicating that the shear wave signal was largely buried in noise. In contrast, the MLS-coded excitation at the same input voltage yielded

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a significantly improved SNR of 5.6 dB, demonstrating the benefit of coded excitation in low-SNR regimes.

Group velocity was estimated by tracking the time-of-flight of the wave peak along the lateral direction. In the high-voltage SP reference case, the measured group velocity was 5.11 m/s with an excellent fit ($R^2 = 1$). In contrast, the SP low-voltage case yielded an unphysical negative group velocity of -8.83 m/s with poor linearity ($R^2 = 0.15$), highlighting the effect of low SNR on temporal tracking. The MLS-coded excitation at low voltage recovered a reliable group velocity of 5.26 m/s with high correlation ($R^2 = 0.93$), consistent with the reference condition.

Phase velocity as a function of frequency was extracted from the (f, c_{ph}) spectra by identifying, at each frequency, the velocity corresponding to the peak spectral amplitude. In the high-voltage SP case, the spectral magnitude map was homogeneous across frequencies, and the phase velocity curve showed stable. For the low-voltage SP excitation, the phase velocity matched the reference at low frequencies but exhibited large fluctuations above 400 Hz, consistent with poor SNR and stronger attenuation of high-frequency shear wave components. In contrast, the MLS-coded excitation preserved a well-defined and continuous phase velocity curve across the full frequency range, closely matching the reference case. This indicates that MLS excitation enhances spectral robustness and allows more accurate estimation of frequency-dependent wave properties, even at low input voltages.

IV. Conclusions

The results presented in this study demonstrate the effectiveness of MLS-coded ARF excitation for improving shear wave elastography (SWE) under low-voltage conditions. By encoding the ARF push with a 127-bit maximal length sequence and applying frequency-domain pulse compression, it was possible to recover high-quality displacement fields with significantly enhanced SNR, phase velocity stability, and group velocity accuracy, even when operating at reduced input voltages.

Conventional single-push excitations at low voltage produced shear wave signals with insufficient SNR, leading to inaccurate group velocity estimates and unstable phase velocity measurements, particularly at higher frequencies. In contrast, the MLS-coded excitation yielded displacement fields comparable in quality to those obtained with high-voltage SP, but without increasing the peak acoustic output. This performance enhancement arises from the cumulative energy delivered by the coded sequence, which—although spread over a longer duration—is temporally compressed into an impulse-like waveform after deconvolution, thus concentrating the signal energy in time without violating safety limits.

Importantly, this method enables SWE measurements in scenarios where conventional ARF-based techniques are limited by regulatory constraints on the mechanical index. Tissues such as neonatal brain, lung parenchyma, or superficial vessels present safety concerns that often preclude the use of high-intensity focused ultrasound. By achieving comparable elastographic performance at lower input voltages, the proposed

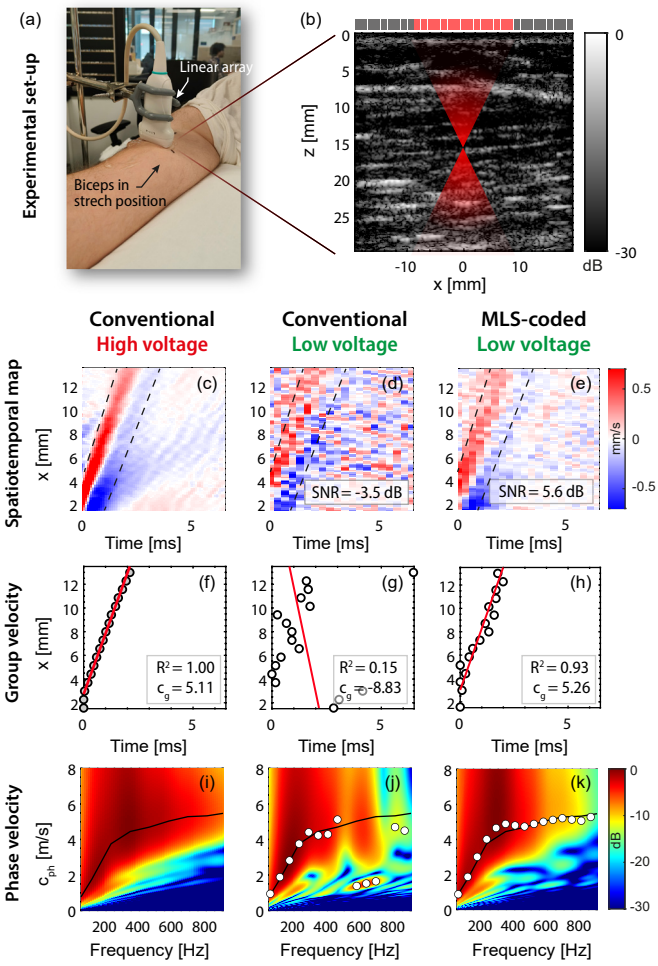


Fig. 2. In vivo evaluation of shear wave propagation in the biceps brachii (a) using three different ARF excitation schemes: (1) single push (SP) with high input voltage (60 V), (2) SP with low voltage (20 V), and (3) 127-bit MLS-coded excitation at low voltage (20 V). (b) B-mode image used for transducer positioning. (c–e) Spatiotemporal propagation maps of axial particle velocity. (f–h) Spatiotemporal shear wave profiles at the ARF focal depth (x, t). Dashed boxes indicate the regions used for SNR computation. (i–k) Phase velocity spectra in the (f, c_{ph}) domain.

MLS-coded approach expands the applicability of ARF-based SWE into these more delicate or sensitive tissues.

In summary, MLS-coded ARF excitation represents a robust and energy-efficient strategy to improve the reliability of SWE under constrained acoustic conditions. Future work will focus on validating this approach in additional clinical scenarios and integrating adaptive excitation schemes to optimize energy delivery according to tissue type and depth.

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