Microsecond-Scale Characterization of Radiation-Induced Dynamics on a 0.35T MR-Linac

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ABSTRACT

Free Radical Generation: occurs across multiple timescales. Analyzing these ultrafast dynamics could provide a predictive tool for adaptive radiotherapy.

Methodology: To achieve this, we configured our scanner to function as a large-scale oscilloscope.

Key findings: Results reveal a dual-nature behavior (noise and medium-dependent interactions) that warrants further research.

INTRODUCTION

Background: MRI detects paramagnetic elements like oxygen and iron. Therefore, MRI and its spatiotemporal information could reflect either free radical generation or tissue reaction, enabling a novel real-time mechanism for adaptive treatments.

Approach: To access ultra-fast timescales, we implemented the SPEEDI[1] sequence with a maximum temporal resolution of 1 μs.

Hardware Optimization: To improve SNR and desynchronization between MRI and Linac hardware components, we included a calibration module to track radiation pulses and predict its location during the imaging module.

[1] Zhong et al "Magnetic Resonance Imaging with Submillisecond temporal resolution" Magnetic Resonance in Medicine, 2020.

MATERIALS AND METHODS

General: MR-Linac Experiments
- Multiple media and MLC configurations
- PRF 135 Hz (~7.41ms) | TR 14.81 ms

Calibration Module:
- No spatial encoding to maximize SNR.
- Facilitates tracking of radiation pulses.
- Enables Synchronization for the imaging module as a post-processing step.
- Evaluation of variability and reproducibility in terms of (PSNR).

Imaging Module:
- After synchronization, a 5 μs window is used to improve temporal SNR.
- This process should make visible the electromagnetic interference (EMI) without distorting other images.

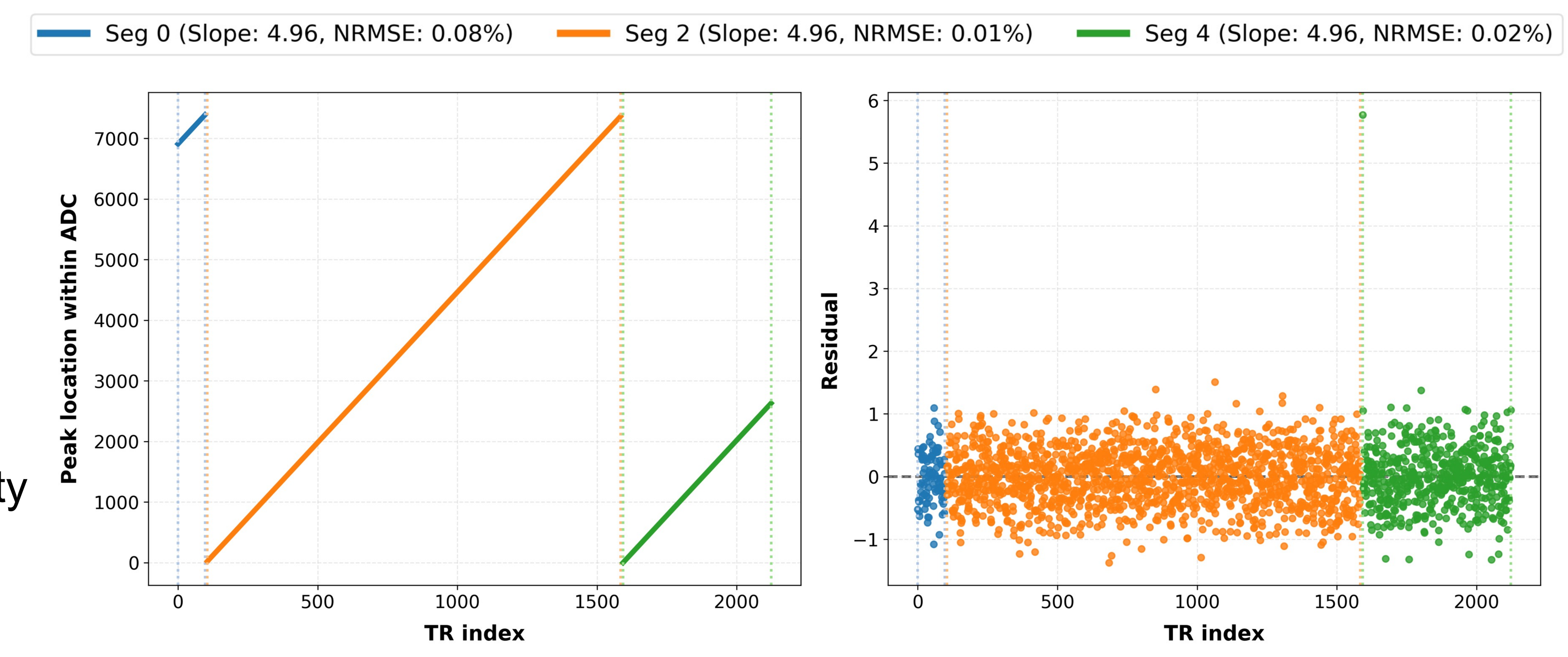
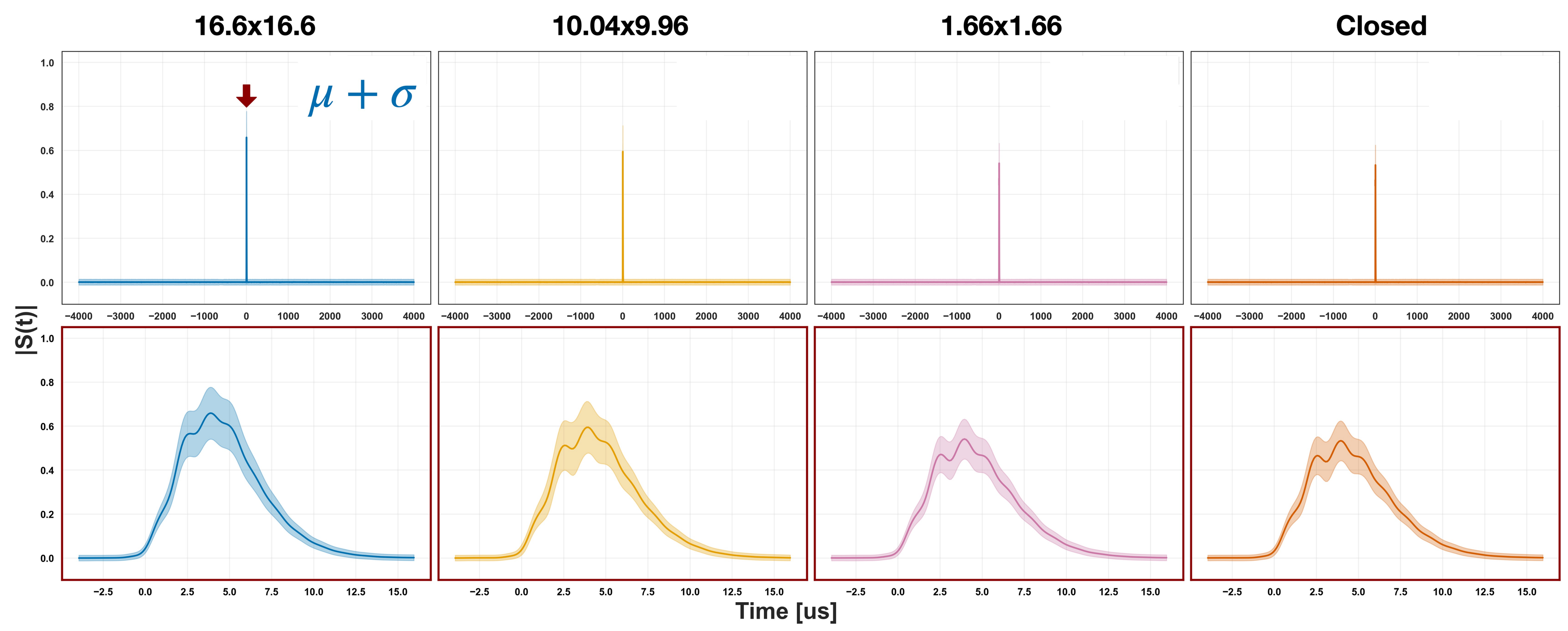


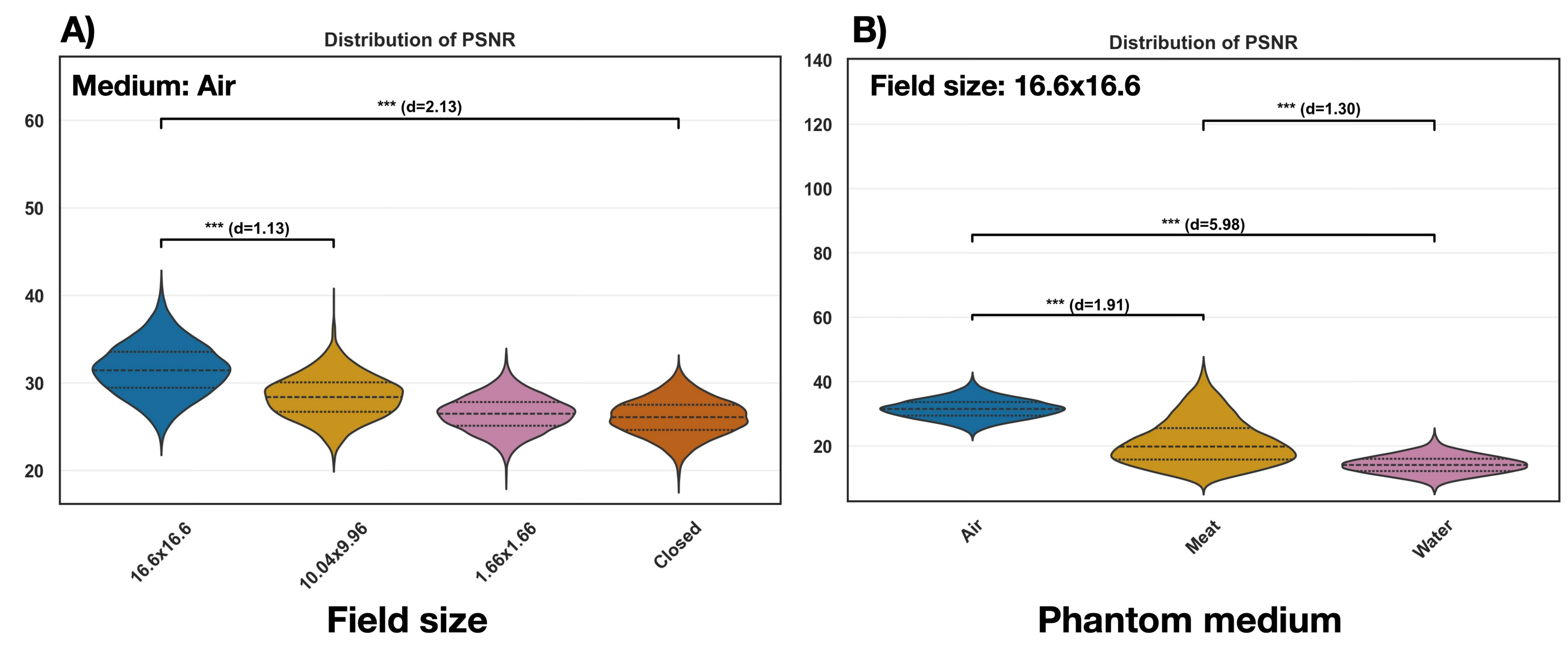
Figure 1: Radiation pulse tracking: curve fitting and residuals. As a first step we used a split-and-merge strategy for multi-linear fitting. Residuals and overall error suggest a strong fit. Please note how the slope 4.96 TR is the difference between TR and PRF.

RESULTS



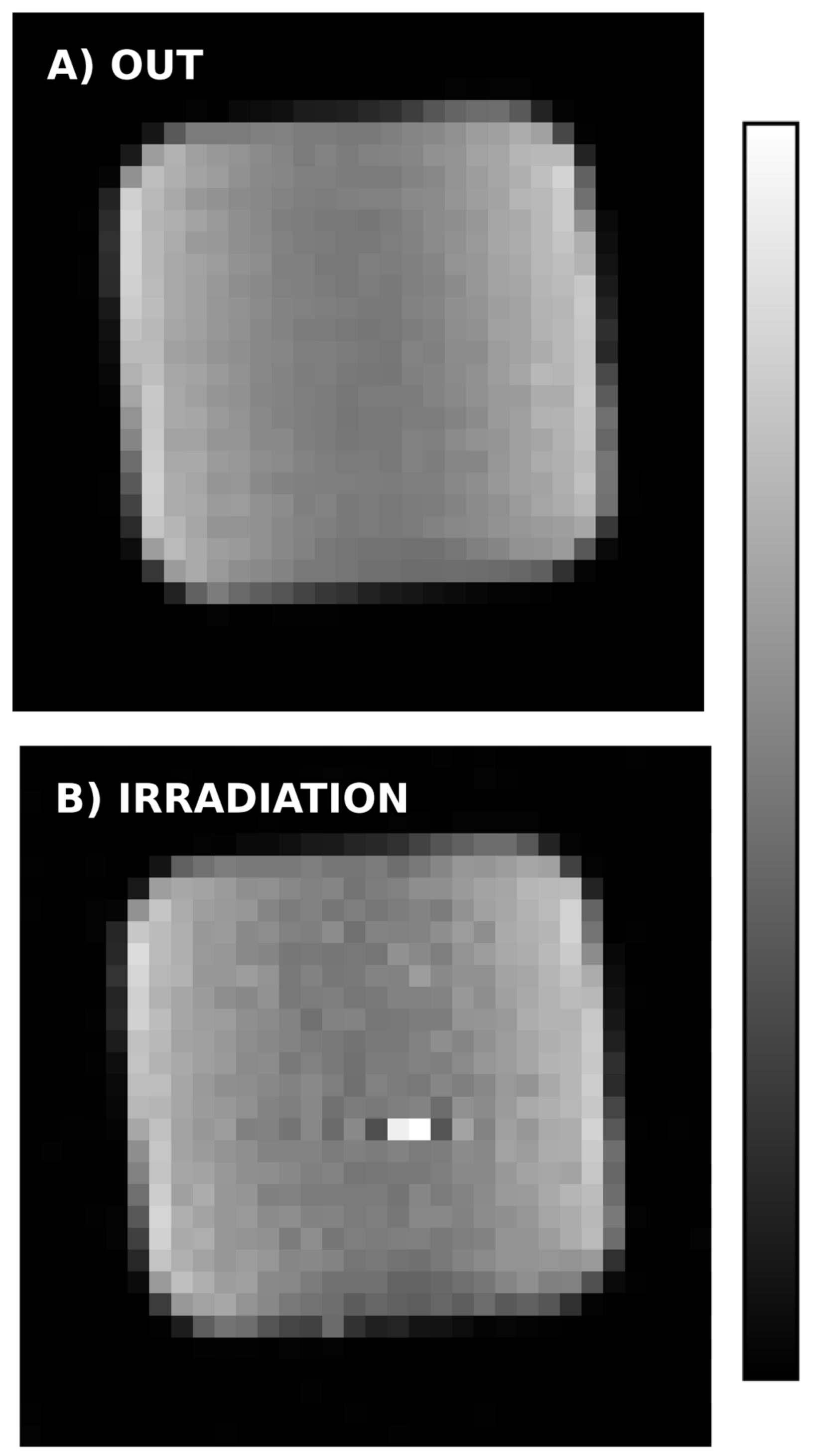
Signal Variation

Figure 2: Microsecond-Scale Characterization of Radiation Spikes. Time-course plots of the absolute MRI signal |S(t)| showing the transient dynamics of radiation-induced events at microsecond resolution. The profile envelope changes distinctively based on the MLC field size configuration. Shaded regions denote standard deviation.



PSNR Distribution

Figure 3: Impact of Field Size and Medium on PSNR. A) Decreasing MLC field size reduces PSNR within an air medium. **B)** Phantom composition significantly alters signal quality at a fixed field size, with water and meat media demonstrating notably lower PSNR distributions compared to air. Significant pairings are annotated with Cohen's effect sizes (d).



EMI and Noise

Figure 4: Visualization of radiation-induced signal perturbations. Panel A) demonstrates the baseline image after offline synchronization. Panel B) captures the raw signal corruption during radiation delivery, providing a unique view of the radiation-induced EMI that remains invisible under standard, asynchronous acquisition.

CONCLUSIONS

We developed a software-based framework that isolates transient radiation effects with microsecond precision, completely avoiding background data corruption. This allows us to demonstrate that **radiation-induced signals are a distinct combination of EMI and ultra-fast dynamics that vary directly with the target medium and MLC configuration.**

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