Compressed Sensing for Accelerated MR Thermometry in MRI-Controlled Transurethral Ultrasound Therapy

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Introduction: MRI-controlled transurethral ultrasound therapy is being developed as a minimally invasive treatment for localized prostate cancer. The technology involves coagulating a targeted region of tissue within the prostate using high intensity ultrasound energy delivered from a transurethral applicator, and controlling the delivery of energy based on real-time MR measurements of the spatial heating pattern. A prototype system comprised of MRI-compatible transurethral applicators, rotational motors, and treatment delivery and control software has been developed and tested [1,2]. A temperature feedback control algorithm which measures the difference between the measured temperature along a target boundary (the "temperature trajectory") and a predefined temperature threshold for thermal coagulation (55°C), adjusts the output parameters of the heating applicator (power, frequency, rotation rate) [3]. The spatial treatment accuracy depends on the ability to obtain accurate measurements of the spatial heating pattern produced during treatment. Currently the 3D spatial pattern of heating is approximated by a series of 2D slices acquired every 5-7 seconds. Knowledge of the true 3D spatial temperature distribution could enable more sophisticated temperature feedback algorithms to be implemented and improve the ability to monitor surrounding tissues for safety. However, the acquisition time for a volume equivalent to the prostate gland is too long for stable control [2,3]. Given that the information in the heating pattern is of low spatial frequency, it suggests that undersampling techniques could be one means of reducing the acquisition time. However it is important for an undersampling technique to preserve the quantitative accuracy of the temperature measurements. Therefore, the objective of this study was to determine if a compressed sensing (CS) based reconstruction method could allow for reduced imaging times without compromising the spatial treatment accuracy of MRI-controlled transurethral ultrasound therapy.

Methods: Fully-sampled 2D Cartesian data was acquired during a heating experiment performed on a Philips 3T scanner (FFE w/EPI Factor=13, TE=15ms, TR=151ms, FOV=256mm, voxel size=1mm x 1mm x 5.3mm, #slices=9; Time=8 sec/image) using a homogenous tissue-mimicking gel phantom and a human prostate boundary. Temperature maps were generated as per the standard PRFS method. After treatment, the temperature measured at the target boundary by the control algorithm (as the device rotated) was recorded. These temperatures are important as they are used by the feedback algorithm to control the delivery of ultrasound energy. Next, the data was radially undersampled by factors of 3x (109 spokes), 6x, 12x, 32x and 57x (6 spokes) in simulation. From this, two new sets of temperature maps were generated: one using a zero-filled inversion and another using a CS reconstruction. The corresponding temperature trajectories were similarly extracted (T_{ZF}, T_{CS}). *Compressed Sensing:* Our CS algorithm implemented the Wotao Split-Bregman L1-minimizer [4] using a Battle-Lemarie wavelet basis for sparsification. Finally, Bioheat Transfer simulations [5] were used to simulate a heating experiment using the same MR imaging parameters. The additional temperature uncertainty introduced by undersampling was described by a Gaussian distribution and the impact of this uncertainty on the spatial accuracy of treatment was evaluated. Treatment accuracy was evaluated as the degree of under- and over-treatment resulting from the zero-filled reconstruction and the CS-reconstruction.

Results: Fig.1 shows example temperature maps from the fully-sampled case along with the ZF and CS-reconstructed cases at 32x acceleration, along with depictions of the treatment boundary and radial sampling pattern. Fig. 2 depicts the over-treatment and under-treatment as obtained through simulations using the temperature noise statistics. There is a trend towards underestimation of the temperature with increasing acceleration factors, which is expected given the blurring out effect of the radial undersampling scheme. This trend is manifested as a tendency to over-treat the boundary in response to the controller's underestimation of the temperature. Overall the effect on the treatment up to 32x is minimal (Fig. 2; Table 1). This reveals the stability of temperature measurements against undersampling artifacts under a radial scheme. As well, these results indicate the robustness of the controller in producing accurate treatments when subject to a noisy temperature environment.

Discussion: Radial undersampling in k-space results in a reduction of the effective field of view. Signal outside this reduced FOV will cause aliasing artifacts in the image. The relatively low frequency nature of the phase data (and the aliasing artifacts associated with it) combined with the subtraction operation results in a surprisingly graceful degradation of the data across a broad range of acceleration factors, up to approximately 32x (Table 1). More importantly, our simulations show the controller is not significantly impacted by this degraded data and the treatment accuracy is not adversely affected. For lower acceleration factors CS may not be necessary; the zero-filled inversion alone still results in good treatment accuracy. However above approximately 12x, the use of a CS-based recovery scheme keeps the temperature error significantly less than that of the ZF inversion. It is noted that there is some alternation in the tendency to overestimate (ex. Table 1, A.F. 22x) or underestimate the temperature. This is likely due to a critical angle effect, whereby due to the variable rotation of the heating pattern, the removal of certain spokes may produce unexpected artifacts. The optimal angular positioning of the spokes may warrant further investigation.

Conclusion: We have demonstrated the robustness of MRI-controlled transurethral ultrasound therapy under high acceleration factors. These results show that the quantitative data obtained through MR temperature maps can remain accurate at very high undersampling factors when reconstructed using a CS methodology. Importantly, there is minimal impact on the treatment accuracy, ensuring the procedure remains safe and effective.

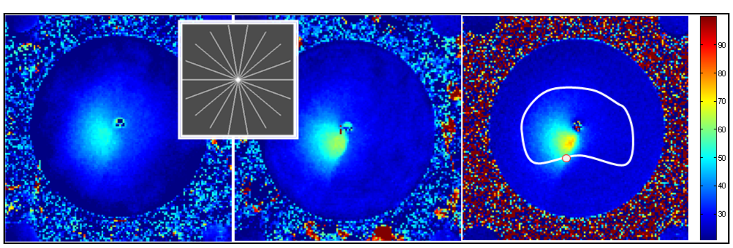

Figure 1: Zero-filled temperature map (left) obtained using 32x radial undersampling (insert). CS-reconstructed temperature map showing noticeable improvement (middle). Fully-sampled temperature map with treatment boundary superimposed (right).

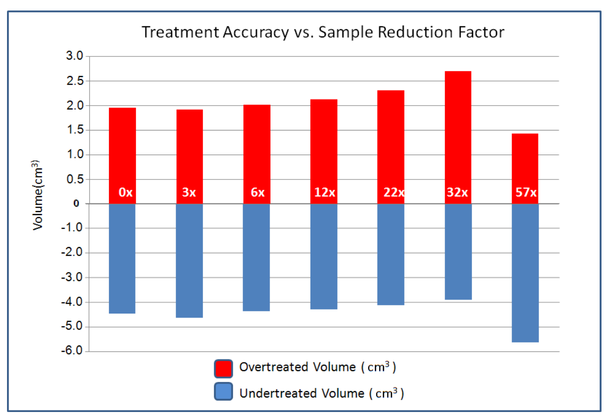

Figure 2: Simulated over-treated and under-treated volumes derived from temperature noise statistics at each acceleration factor. The first bar (0x) represents the treatment error incurred in the fully-sampled case.

Acceleration Factor-	**3x**	**6x**	**12x**	**22x**	**32x**	**57x**
[ZF] Total Mistreated Volume, (cm^3)	6.55	6.47	6.50	6.82	6.80	7.79
[ZF] %Change in Volume from 0x	2.1%	0.8%	1.3%	6.3%	5.9%	21.3%
[CS] Total Mistreated Volume, (cm^3)	6.55	6.39	6.42	6.45	6.61	7.06
[CS] %Change in Volume from 0x	2.1%	0.4%	0.0%	0.5%	3.0%	10.0%

Table 1: Simulation results summary for each of the ZF and CS cases across acceleration factors. Total mistreated volume is the magnitude sum of the under-treated and over-treated volumes.

References:

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