

PhD Thesis Title: WHOLE BODY AND UPPER EXTREMITY ULTRA-HIGH FIELD MAGNETIC RESONANCE IMAGING: COIL DEVELOPMENT AND CLINICAL IMPLEMENTATION

Author: Shailesh B. Raval, M.S., Ph.D.

Email: RSHAILESH8504@gmail.com, SBR15@pitt.edu

Institution: University of Pittsburgh

Supervisor: Dr. Tamer S. Ibrahim, Ph.D.

Committee Members: Dr. Vijay S. Gorantla, M.D., Ph.D.; Howard J. Aizenstein, M.D., Ph.D.; George D. Stetten, M.D., Ph.D.

Graduation Date: July 11th, 2016

Available Online: http://d-scholarship.pitt.edu/32877/7/ShaileshBRaval_ETDPITT27July2017_1.pdf

ABSTRACT:

Ever since Magnetic Resonance Imaging(MRI)'s introduction, MRI has become one of the most promising non invasive methods in evaluating, identifying healthy and diseased conditions in the human body [1-8,11,13,14,15-20,21-27,29-35]. In the recent two decades, research groups (4 Tesla (T) – 23.5 T and higher) have been working on addressing the ultra-high field (UHF) imaging challenges in humans and discovering that it could provide anatomical, functional and physiological information beyond just gains in Signal to noise ratio (SNR). Initially, major efforts have been focused on imaging the brain in contrast to body/torso (including specific extremities), so there requires tremendous attention towards abdominal and extremity imaging too. Whole Body and upper extremity imaging exams are increasingly growing as a part of the total clinical MRI exams at lower field (≤ 3 T) and has translated towards UHF because of its glorious promises [1,2,5,7,20-22,24]. Though, some artifacts and technical challenges do exist [2,5-8,10,11, 19-22,23-35]. In recent years, ultra-high field, such as 7 T, has shown its inherent ability to improve the SNR, scan time and higher anatomical resolution [1-9,10,11,14-20,21-27,28-35]. Human head, prostate, cardiac, spine, kidney, liver, extremity and human torso (abdominal) imaging have been investigated at 7 T and have demonstrated high caliber imaging.

The original research and development works presented here consists of: First, the multi-channel high density transmit (Tx) coil will be based on the innovative tic tac toe (TTT) design [6-8,10,11,14,24,32] which possesses a load insensitive and highly coupled characteristic in terms of magnetic and electric field distributions. The simulation and experiment B_1^+ profile in phantom show excellent correlation, which displays the accuracy of Finite Difference Time Domain (FDTD) prediction. The noise correlation exhibited par excellence isolation and the G factor depicted the high parallel imaging capability. Also, the 7T in vivo imaging with Tx Rx Array configuration in contrast to Tx configuration showing an increase of 3 to ~ 3.5 times in SNR in human Whole body applications. 3D InVivo images were acquired and clinical applications were implemented successfully with excellent anatomical detail [6-8,15-22, 10,11,13,23-25,27-35] in Whole body as abdominal/torso organs imaging. As a part of the extremity imaging, we developed a transverse electromagnetic (TEM) coil as a transmitter in conjunction with multi channels (CH) Rx, the only insert for Hand/Wrist/Forearm imaging [1-5, 15-22] as extremity (in contrast to none existed in commercial market). We also acquired the interdisciplinary set of sequences (not just typical T1 and T2 weighted imaging protocols, post-processing methods) to extract the specific anatomy from

high resolution scans ultimately helping to explore new clinical applications and add knowledge to existing applications. These radio frequency (microwave) systems will enhance the fundamental scientific knowledge of RF coil design approach at higher, ultra-high and extremely higher frequency, moreover it adds to the realm of clinical applications resulting in contributing to the economy and even more to the improving the medicine and healthcare.

References to author publications that relate specifically to the dissertation:

1. **Raval, S.B.**, Zhao, T., Krishnamurthy, N., Santini, T., Britton, C., Gorantla, V. S., and Ibrahim, T. S. (2016) Ultra-high-field RF coil development for evaluating upper extremity imaging applications. *NMR Biomed.*, 29: 1768–1779. doi: 10.1002/nbm.3582.
2. **Raval S.B.**, Britton C.A., Zhao T., Krishnamurthy N., Santini T., Gorantla V.S., Ibrahim T.S. (2017) Ultra-high field upper extremity peripheral nerve and non-contrast enhanced vascular imaging. *PLoS ONE* 12(6): e0175629. <https://doi.org/10.1371/journal.pone.0175629>
3. **Raval, S.B.**, Zhao, T., Zhao, Y., Ibrahim, T.S., Gorantla, V.S., Upper Extremity Ultra-High Field MR Imaging of Bilateral Hand Transplant Patient: Case Report (VCA), *Plastic and Reconstructive Surgery*: October 2015 - Volume 136 - Issue 4S - p 29–30, doi: 10.1097/01.prs.0000472310.97888
4. **Raval, S.B.**, Zhao, T., Krishnamurthy, N., Ibrahim, T.S., Gorantla, V.S. “RF System for Ultra-High Field Upper Extremity Imaging” *Plastic and Reconstructive Surgery*, October 2015, 136 (4S), 81, doi: 10.1097/01.prs.0000472381.50361.f6
5. **Raval, S.B.**, Zhao, T., Krishnamurthy, N., Ibrahim, T.S., Gorantla, V.S., “Exploring Peripheral Nerve, Macro and Micro-Vasculature Imaging Applications at Ultra-High Field MRI.” *Plastic Reconstructive Surgery*, October 2015, 136 (4S), 20, doi: 10.1097/01.prs.0000472298.54825.5f.
6. **Raval, S.B.**, Santini, T., Wood, S., Krishnamurthy, N., Zhao, T., Ibrahim, T.S. “In-vivo (8x4) 32 channel Tx-Only Body Array for UHF MRI” in *Proc. of the 23rd International Society of Magnetic Resonance in Medicine Annual Meeting, Toronto, Canada, May 2017.*
7. **Raval, S.B.**, Zhao, T., Krishnamurthy, N., Zhao, Y., Wood, S., Bae, K-T., Ibrahim, T.S., “Initial Results: Ultra-High Field 32-ch Tx Body Array with Bright Centers” in *Proc. of The 23rd International Society of Magnetic Resonance in Medicine Annual Meeting, Toronto, Canada, May 2015.*
8. **Raval S.B.**, Zhao Y., Zhao, T., Krishnamurthy, N., Wood, S., Ibrahim, T.S. “7T Tx Body Coil with Rx-Only Insert: Preliminary Results” in *Proc. of the 21st International Society of Magnetic Resonance in Medicine Annual Meeting, Utah, May 2013.*
9. Ercument, V.E., Sahin, H., Oksuz, S., Dong, L., Miller, M.R., Shojaati, G., Wollstein, G., Chan, K.C., Sigal, I., Kostereva, N., **Raval, S.B.**, Ibrahim, T.S., Goldberg, J.L., Benowitz, L., Schuman, J.S., Zor, F., Solari, M., Washington, K.M., Gorantla, V.S., “A Preclinical Swine Model for Whole Eyeball Transplantation - Planning and Procedural Aspects”. In *Proc. Of The ASRT 5th Biennial Meeting: November 2016 in Chicago, Illinois*
10. Zhao, Y., Zhao, T., **Raval, S.B.**, Krishnamurthy, N., Zheng, H., Harris, C. T., Handler, W.B., Chronik, B.A., Ibrahim, T. S. (2015). Dual Optimization Method of RF and Quasi-Static Field Simulations for Reduction of Eddy Currents Generated on 7T RF Coil Shielding. *Magnetic Resonance in Medicine*, 74(5), 1461–1469. <http://doi.org/10.1002/mrm.25424>

11. Santini, T.R., Krishnamurthy, N., Wood, S., **Raval, S.B.**, Zhao, Y., Fischetti, A., Koo, M., Aizenstein, H.J., Ibrahim, T.S., 64-channel Double-Octagon Tx Head Coil for 7T Imaging. Proc. Intl. Soc. Mag. Reson. Med. 25 (2017) 4308. doi: 10.1016/j.mri.2017.09.005.
12. Wood S, Krishnamurthy N, Santini T, **Raval S**, Farhat N, Holmes JA, et al. (2017) Design and fabrication of a realistic anthropomorphic heterogeneous head phantom for MR purposes. PLoS ONE 12(8): e0183168. <https://doi.org/10.1371/journal.pone.0183168>
13. Krishnamurthy, N., Stough, D., Zhao, T., **Raval, S.B.**, Boada, F., Ibrahim, T.S., “B1+ and Coupling Variability of Transmit Head Coils and Arrays for Ultra-High Field MRI: Simulation Studies and Experiments. Proc. Intl. Soc. Mag. Reson. Med. 20. 2012
14. Santini, T.S., Kim, J-H., Wood, S., Krishnamurthy, N., Farhat, N., Maciel, C., **Raval, S.B.**, Ibrahim, T.S. “A new RF Transmit Coil for Foot and Ankle Imaging at 7T MRI”. Magnetic resonance imaging 45, 1-6, January 2018.
15. **Raval, S.B.**, Zhao, T., Krishnamurthy, N., Ibrahim, T.S., Gorantla, V.S., “Ultra-high Resolution Non-Contrast Vascular and Nerve Imaging for Graft Monitoring and Procedural Planning in Reconstructive Transplantation”, in Proc. Of the Military Health System Research Symposium (MHSRS), Florida, 2016.
16. **Raval, S.B.**, Zhao, T., Zhao, Y., Ibrahim, T.S., Gorantla, V.S., “Non-contrast enhanced 7 tesla MR imaging for non-invasive monitoring of chronic rejection in reconstructive transplantation”, Vascularized Composite Allotransplantation, 2016, 3 (1-2), 21-22, Published online: 19 Oct 2016
17. **Raval, S.B.**, Zhao, T., Krishnamurthy, N., Ibrahim, T.S., Gorantla, V.S., “Ultra-high field upper extremity peripheral nerve and non-contrast vascular imaging at 7T tesla high resolution MRI”, in Proc. Of the 12th International hand and Composite Tissue Allotransplantation Society Annual Meeting, Philadelphia, April 2015.
18. **Raval, S.B.**, Zhao, T., Zhao, Y., Gorantla, V.S., Ibrahim, T.S., “Ultrahigh field(7T) magnetic resonance musculoskeletal imaging in upper extremity allotransplantation – first report in VCAMRI after upper extremity transplantation”, in Proc. Of the 12th International hand and Composite Tissue Allotransplantation Society Annual Meeting, Philadelphia, April 2015.
19. **Raval, S.B.**, Zhao, T., Krishnamurthy, N., Santini, T., Gorantla, V.S., Ibrahim, T.S., “RF System for Ultra-High Field Upper Extremity Imaging”, in 10th Biennial meeting at Center for Magnetic Resonance research, Minneapolis, Nov 2015.
20. V. S. Gorantla, MD, PhD, ***S. B. Raval, M.S., Ph.D.**, M. Davis, M. D., T. Ibrahim, PhD, “Regenerative Medicine and Advanced Rehabilitation – Today and in Future”, “UHR NCE Vascular and Nerve Imaging for Graft Monitoring and Procedural Planning in Reconstructive Transplantation”. RESTOR™ Program – University of Pittsburgh, Pittsburgh, Pennsylvania. US Army Institute of Surgical Research, Joint Base San Antonio (Fort Sam Houston, Lackland Base, Randolph Base), Texas. NATO CSO-HFM-272 SYMPOSIUM, Brussels, Belgium, October 17-20, 2016.
21. **Raval, S.B.**, Zhao, T., Krishnamurthy, N., Santini, T., Gorantla, V.S., Ibrahim, T.S., “Upper extremity neural and vascular imaging with UHF 7T MRI,” Podium presentation in Proc. of the 23rd International Society of Magnetic Resonance in Medicine Annual Meeting, Toronto, Canada, May 2015.
22. **Raval, S.B.**, Zhao, T., Zhao, Y., Gorantla, V.S., Ibrahim, T.S., “Ultrahigh field MRI after upper extremity transplantation”, in Podium presentation in Proc. of the 23rd International Society of Magnetic Resonance in Medicine Annual Meeting, Toronto, Canada, May 2015.

23. Krishnamurthy, N., Zhao, Y., Kim, J-H., **Raval, S.B.**, Zhao T., Ibrahim, T.S. "T2* Susceptibility Weighted and Echo- Planar Imaging at 7T using RF Shimming" in Proc. of the 23rd International Society of Magnetic Resonance in Medicine Annual Meeting, Toronto, Canada, May 2015.
24. Ibrahim, T.S., Santini, T., **Raval, S.B.**, Krishnamurthy, N., Wood, S., Kim, J-H., Zhao, T., Wu, X.S., Yacoub, E.S., Aizenstein, H.J., Zhao, T., "Towards Homogeneous 7T neuro Imaging and Comparisons between 7T TTT and NOVA RF Coil Systems", in Proc. of the 25th International Society of Magnetic Resonance in Medicine Annual Meeting, Honolulu, April 2017.
25. Krishnamurthy, N., Zhao, Y., **Raval, S.B.**, Kim, J-H., Wood, S., Santini, T., Zhao, T., Ibrahim, T.S., "7T Multi-Slab Whole-Head Homogenous and Low SAR T2 Acquisitions" in Proc. of the 23rd International Society of Magnetic Resonance in Medicine Annual Meeting, Toronto, Ontario, May-June 2015.
26. Schirda, C., Zhao, T., **Raval, S.B.**, Lee, S., Arslanian, S., Hetherington, H., Ibrahim, T.S., "Functional 2D 31P MRSI in the leg during exercise, using a dual-tuned 1H/31P volume coil" in Proc. of the 23rd International Society of Magnetic Resonance in Medicine Annual Meeting, Toronto, Ontario, May-June 2015.
27. Wood, S., Santini, T., Krishnamurthy, N., **Raval, S.B.**, Ibrahim, T.S., "Evaluation of Anthropomorphic phantom with In-vivo using Quantitative MRI", in Proc. of the 25th International Society of Magnetic Resonance in Medicine Annual Meeting, Honolulu, April 2017.
28. Wood, S., Krishnamurthy, N., Zhao, Y., **Raval, S.B.**, Zhao, T., Holmes, J.A., Ibrahim, T.S. "Anatomically Detailed Human Head Phantom for MR", in Proc. of the 22nd International Society of Magnetic Resonance in Medicine Annual Meeting, Milan, May 2014.
29. Zhao, Y., Krishnamurthy, N., Wood, S., Zhao, T., **Raval, S.B.**, Ibrahim, T.S., "3D eigenmodes optimizations for 3D imaging at 7T" in Proc. of the 23rd International Society of Magnetic Resonance in Medicine Annual Meeting, Toronto, Ontario, May-June 2015.
30. Krishnamurthy, N., Zhao, Y., Maccloud, R., Zhao, T., **Raval, S.B.**, Kim, J., Rosano, C., Aizenstein, H.J., Ibrahim, T.S. "Segmentation of Small Veins Using 3D isotropic SW images at 7T" in Proc. of the 22nd International Society of Magnetic Resonance in Medicine Annual Meeting, Milan, May 2014.
31. Krishnamurthy, N., Wood, S., Kim, J-H., Zhao, Y., **Raval, S.B.**, Zhao, T., Ibrahim, T.S. "Transmit Array Performance across Subjects at 7T MRI: Simulations and Experiments" in Proc. of the 22nd International Society of Magnetic Resonance in Medicine Annual Meeting, Milan, May 2014.
32. Ibrahim, T.S., Zhao, Y., Krishnamurthy, N., **Raval, S.B.**, Zhao, T., Wood, S., Kim, J-H., "20-to-8 Chanel Tx Array with 32 channels adjustable receive-only insert for 7T Head Imaging", in Proc. of the 21st International Society of Magnetic Resonance in Medicine Annual Meeting, Utah, May 2013.
33. Krishnamurthy, N., Zhao, Y., Kim, J-H., **Raval, S.B.**, Zhao, T., Ibrahim, T.S. "7T Multi-Slab Whole-Head Homogenous and Low SAR T2 Acquisitions" Pittsburgh Imaging Community Retreat – Mellon Institute CMU, Pittsburgh, May 2014.
34. Zhao, Y., Zhao, T., Wood, S., Krishnamurthy, N., **Raval, S.B.**, Kim, J-H., Ibrahim, T.S., "3D SAR-Constrained Homogeneous B1+ Field at 7T" in Proc. of the 21st International Society of Magnetic Resonance in Medicine Annual Meeting, Utah, May 2013.
35. Krishnamurthy, N., **Raval, S.B.**, Zhao, Y., Wood, S., Zhao, T., Ibrahim, T.S., "Experiment and Simulation Validation of the effect of 32 Channel Receive Array Inserts on Transmit B1+ and SAR

at 7Tesla Parallel Transmit System” in Proc. of the 21st International Society of Magnetic Resonance in Medicine Annual Meeting, Utah, May 2013.