5-1-2012

# Water-silicone separated volumetric MR acquisition for rapid assessment of breast implants

Ananth J. Madhuranthakam
*GE Healthcare, UK*

Martin P. Smith
*Harvard Medical School*

Huanzhou Yu
*GE Healthcare, United States*

Ann Shimakawa
*GE Healthcare, United States*

Scott B. Reeder
*University of Wisconsin-Madison*

*See next page for additional authors*

Citation of this paper:
Madhuranthakam, Ananth J.; Smith, Martin P.; Yu, Huanzhou; Shimakawa, Ann; Reeder, Scott B.; Rofsky, Neil M.; McKenzie, Charles A.; and Brittain, Jean H., "Water-silicone separated volumetric MR acquisition for rapid assessment of breast implants" (2012). *Paediatrics Publications*. 2729.
https://ir.lib.uwo.ca/paedpub/2729

## Authors

Ananth J. Madhuranthakam, Martin P. Smith, Huanzhou Yu, Ann Shimakawa, Scott B. Reeder, Neil M. Rofsky, Charles A. McKenzie, and Jean H. Brittain

JOURNAL OF MAGNETIC RESONANCE IMAGING 35:1216–1221 (2012)

**Technical Note**

# Water-Silicone Separated Volumetric MR Acquisition for Rapid Assessment of Breast Implants

Ananth J. Madhuranthakam, PhD,[1]* Martin P. Smith, MD,[2] Huanzhou Yu, PhD,[3]
Ann Shimakawa, MS,[3] Scott B. Reeder, MD, PhD,[4] Neil M. Rofsky, MD,[2]
Charles A. McKenzie, PhD,[5] and Jean H. Brittain, PhD[6]

**Purpose:** To develop a robust $T_2$-weighted volumetric imaging technique with uniform water-silicone separation and simultaneous fat suppression for rapid assessment of breast implants in a single acquisition.

**Materials and Methods:** A three-dimensional (3D) fast spin echo sequence that uses variable refocusing flip angles was combined with a three-point chemical-shift technique (IDEAL) and short tau inversion recovery (STIR). Phase shifts of $-\pi/6$, $+\pi/2$, and $+7\pi/6$ between water and silicone were used for IDEAL processing. For comparison, two-dimensional images using 2D-FSE-IDEAL with STIR were also acquired in axial, coronal, and sagittal orientations.

**Results:** Near-isotropic (true spatial resolution—$0.9 \times 1.3 \times 2.0$ mm$^3$) volumetric breast images with uniform water-silicone separation and simultaneous fat suppression were acquired successfully in clinically feasible scan times (7:00–10:00 min). The 2D images were acquired with the same in-plane resolution ($0.9 \times 1.3$ mm$^2$), but the slice thickness was increased to 6 mm with a slice gap of 1 mm for complete coverage of the implants in a reasonable scan time, which varied between 18:00 and 22:30 min.

**Conclusion:** The single volumetric acquisition with uniform water and silicone separation enables images to be reformatted into any orientation. This allows comprehensive assessment of breast implant integrity in less than 10 min of total examination time.

**Key Words:** implant; silicone; breast; 3D FSE; IDEAL
**J. Magn. Reson. Imaging 2012;35:1216–1221.**

SILICONE BREAST IMPLANTS are used for cosmetic purposes and for breast reconstruction in women who have undergone mastectomy. Recommendations to regularly monitor these implants derive from the fact that many ruptures are asymptomatic and those that are intracapsular can be difficult to diagnose clinically (1,2). MRI has been the imaging modality of choice to detect silicone implant ruptures (3,4). Recently, the US Food and Drug Administration (FDA) has mandated that the silicone implant package and patient labeling should include a need for regular MRI screening to detect occult rupture (5). The labeling further states that a woman should have her first MRI 3 years after the initial implant surgery and every 2 years thereafter. According to the American Society of Plastic Surgeons, approximately 300,000 breast augmentation procedures are performed each year (e.g., 307,230 in 2008) in the United States (6). This highlights a need for a robust and rapid MRI technique to visualize silicone ruptures.

Various MRI techniques have been developed for silicone implant assessment. With the long $T_1$ and $T_2$ relaxation times of silicone (7), $T_2$-weighted contrast is typically preferred to visualize silicone, which appears bright on these images (8). The most commonly used sequences include $T_2$-weighted acquisitions with both frequency-selective water suppression and short tau inversion recovery (STIR) for fat suppression (9,10). This approach generates silicone-only images with bright signal. To assess the remainder of the breast anatomy surrounding the implants, including the fibrous capsule, water-only $T_2$-weighted images (fat and silicone suppressed) are acquired typically. While these techniques have been used routinely in clinical practice, frequency-selective suppression

---

[1]Global Applied Science Lab, GE Healthcare, Boston, Massachusetts, USA.
[2]Department of Radiology, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, Massachusetts, USA.
[3]Global Applied Science Lab, GE Healthcare, Menlo Park, California, USA.
[4]Departments of Radiology, Medical Physics, Biomedical Engineering, and Medicine, University of Wisconsin, Madison, Wisconsin, USA.
[5]Department of Medical Biophysics, University of Western Ontario, London, Ontario, Canada.
[6]Global Applied Science Lab, GE Healthcare, Madison, Wisconsin, USA.
Dr. Rofsky's current affiliation is Department of Radiology, UT Southwestern Medical Center, Dallas, Texas, USA.
*Address reprint requests to: A.J.M., Ansin-241, Beth Israel Deaconess Medical Center, 330 Brookline Avenue, Boston, MA 02215. E-mail: ananth.madhuranthakam@ge.com

Received February 26, 2011; Accepted October 4, 2011.
DOI 10.1002/jmri.22872

pulses are prone to failure in the presence of $B_0$ inhomogeneities (11).

To render the images insensitive to $B_0$ inhomogeneities, multi-point chemical shift-based techniques have been proposed for silicone imaging. Earlier techniques were based on the approximation that the resonance frequency difference between water and fat is a multiple of the resonance frequency difference between fat and silicone (12,13). This technique provided images with uniform separation of silicone, but one of the reconstructed images contained both water and fat. Recently, STIR has been combined with multi-point chemical shift-based techniques to suppress fat, while also separating water and silicone (14,15). In a clinical setting, this has been shown to produce fat-suppressed, water-only, and silicone-only images consistently and more reliably than traditional techniques (15). All of these techniques, however, have been 2D acquisitions with limited spatial resolution in the slice direction. This necessitates lengthy examination times with multiple two-dimensional (2D) acquisitions in separate planes to ensure adequate visualization of the implants.

The purpose of this work was to develop a robust fat-suppressed 3D $T_2$-weighted acquisition that provides volumetric water-only and silicone-only images with uniform separation for rapid assessment of breast implants. Such volumetric acquisitions hold promise to provide adequate information to evaluate the breast implant integrity in a single acquisition.

## MATERIALS AND METHODS

### *Subjects*

The study was approved by the institutional review board and was compliant with Health Insurance Portability and Accountability Act (HIPAA). Written informed consent was obtained from all subjects before imaging. Seven women with known breast implants (age range, 36–62 years; mean, 53 years) were imaged.

### *Image Acquisition and Reconstruction*

For confident diagnosis of breast implants, silicone must be differentiated from normal breast tissues composed of water and fat. Fortunately, silicone has a distinct MR frequency, which is approximately 4.5 ppm upfield of water and 1.2 ppm upfield of the main methylene peak of fat (approximately 310 Hz lower than water and 100 Hz lower than fat at 1.5 Tesla [T]) (13). Silicone also has long $T_1$ (~850 ms at 1.5T) and $T_2$ (~160 ms at 1.5T) relaxation times (7).

The image acquisition and reconstruction strategy consisted of three distinct aspects. First, the image acquisition was based on a modulated 3D fast spin echo (FSE) pulse sequence that uses variable refocusing flip angles and extended echo trains. Traditionally, high refocusing flip angles (e.g., $\geq 130°$) are used in FSE readout, which limits the total number of echoes that can be acquired before signal diminishes. However, it has been demonstrated previously that the effective signal decay can be prolonged by modulating the refocusing flip angles (16–18). Recent studies have used such modulated refocusing flip angles over very long echo trains to acquire 3D $T_2$-weighted images in clinically feasible scan times (19–21).

Second, a STIR pulse was used in front of the modulated 3D FSE acquisition to suppress fat. An adiabatic hyperbolic secant pulse (22) was used to minimize sensitivity to $B_1$ inhomogeneities, which are often encountered in breast imaging. Third, a multi-point chemical shift-based technique known as Iterative Decomposition of water and fat with Echo Asymmetry and Least squares estimation (IDEAL) was used to separate water and silicone. IDEAL acquires three or more echoes with different relative phase for the chemical species of interest, and uses an iterative reconstruction algorithm to decompose the chemical species into separate images. Because IDEAL determines the local field map due to $B_0$ inhomogeneities, it decomposes the chemical species robustly even in the presence of $B_0$ inhomogeneities and maximizes SNR in the reconstructed images for all combinations of the separated chemical species in a voxel (23). For example, IDEAL has been shown to produce uniformly separated water and fat images with multiple sequences in various anatomies including areas with high $B_0$ variation such as the brachial plexus (24,25).

### *MRI Experiments*

All imaging was performed on a 1.5T scanner (GE Healthcare, Waukesha, WI) using an eight-channel phased-array breast coil (GE Healthcare, Aurora, OH) for signal reception. An investigational version of an IDEAL reconstruction algorithm was modified to separate water and silicone. For IDEAL processing, three echoes with water-silicone phase shifts of $-\pi/6$, $+\pi/2$ and $+7\pi/6$ with respect to spin echo were acquired to maximize noise performance (23,26). The echo times corresponding to these phase shifts between water and silicone (310 Hz apart at 1.5T) were −0.26 ms, +0.80 ms, and +1.88 ms, respectively. The modulated 3D FSE pulse sequence was modified to acquire these phase-shifted echoes by shifting the readout gradient with respect to CPMG echo (27,28). The complex phase-shifted echoes were first reconstructed using the Fourier transform to generate the source images, followed by the IDEAL processing to reconstruct water-only and silicone-only images. The water-only and silicone-only images were later chemical-shift corrected and recombined to form images with the water and silicone signals in-phase and out-of-phase. The typical scan parameters were as follows: 3D axial acquisition, field of view (FOV) = $300 \times 300$ mm$^2$, slice thickness = 2.0 mm, No. of slices = 98, repetition time (TR) = 2000 ms, $TE_{eff}$ = 100 ms, and ETL = 64. Frequency and phase encoding steps were varied between 224 and 320 to achieve a true spatial resolution of approximately $0.9 \times 1.3 \times 2.0$ mm$^3$ (interpolated to $0.6 \times 0.6 \times 1.0$ mm$^3$). Of the acquired 98 slices, the outermost two slices on either side were omitted after reconstruction due to slice warping. An inversion time of 200 ms was used with STIR to suppress fat. An auto-calibrated parallel

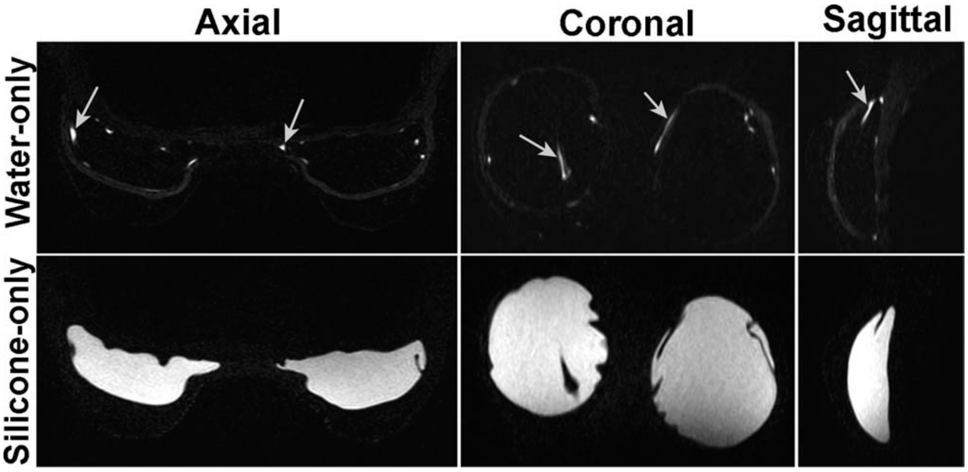

**Figure 1.** Uniformly separated water-only and silicone-only images of a 36-year-old normal volunteer. Images were acquired in the axial plane and reformatted into coronal and sagittal orientations, all from a single 10:00 minute acquisition. The arrows highlight the fluid between the implant and the fibrous capsule, which is a common and normal finding. Image parameters were as follows: FOV = 300 × 300 $mm^2$, matrix = 320 × 224, slice thickness = 2 mm, spatial resolution = 0.9 × 1.3 × 2.0 $mm^3$, reconstructed to 0.6 × 0.6 × 1.0 $mm^3$.

imaging technique (29) was used to accelerate the image acquisition by a factor of 2.7, further reducing scan time to between 7:00 and 10:00 min. In all subjects, two-dimensional images were also acquired using 2D-FSE-IDEAL with STIR (15) in axial, sagittal and coronal orientations for comparison. The parameters with 2D acquisitions were maintained to achieve the same in-plane resolution as the 3D acquisitions (0.9 × 1.3 $mm^2$) but the slice thickness had to be increased to 6 mm with a slice gap of 1 mm for complete coverage of the implants in a reasonable scan time. The total scan time for complete coverage of both breasts with 2D acquisitions varied between 18:00 and 22:30 min.

## RESULTS

Fat-suppressed $T_2$-weighted volumetric images with uniform water-silicone separation were acquired successfully in all volunteers. A representative example of water and silicone separated breast images of a volunteer is shown in Figure 1. High spatial resolution along the slice direction and contiguous slices afforded by the 3D acquisition enabled the images to be reformatted into other standard orientations. The folds of the implants are clearly visible in all orientations. The bright signal on the water-only images (arrows) is the fluid between the silicone implant and the fibrous capsule. The adiabatic inversion pulse used for STIR provided uniform fat suppression throughout the volume.

Figure 2 shows an intact unilateral breast implant of a different volunteer. Water-only (Fig. 2a) and silicone-only (Fig. 2b) images can be combined to form in-phase (Fig. 2c) and out-of-phase (Fig. 2d) contrasts. The in-phase image represents the combined water and silicone with fat-suppression, which is helpful in defining the entire anatomy of the breast with respect to silicone. This is especially helpful in localizing extracapsular ruptures, when present. The out-of-phase image is of limited known clinical value but accentuates the boundaries between the implant and the fluid.

Figure 3 shows a double-lumen saline-silicone implant in the left breast and a single-lumen silicone implant in the right breast of a different volunteer. The fluid appears on the water-only images uniformly around the implant in the left breast while it is sparsely distributed in the right breast. It demonstrates clearly that the left breast has a double-lumen implant, where the inner silicone implant is encompassed by an outer saline implant. The sparsely distributed fluid in the right breast is the normal fluid accumulation surrounding the single-lumen silicone implant inside the fibrous capsule.

A comparison of 3D and 2D acquisitions from another volunteer is shown in Figure 4. Axial 3D images were acquired and reformatted into coronal and sagittal orientations, all from a single acquisition. Orthogonal 2D images were acquired separately in multiple orientations for complete assessment of the implants. Both 3D and 2D images were acquired with IDEAL and hence produce silicone-only images with uniform separation. The total scan time for all 2D acquisitions was 18:10 min for adequate coverage of both breasts compared with 7:02 min for the single 3D acquisition.

Figure 5 shows water-only and silicone-only images from a different volunteer, exhibiting linguine signs (arrows) within the implant, resulting from intracapsular rupture. The volumetric nature of the acquisition allows tracking of the implant capsule throughout the volume which may increase the diagnostic confidence. The intracapsular rupture is contained within the fibrous capsule, with some collapsed folds trapping water and debris visible on the water-only images in all orientations (arrowheads).

## DISCUSSION

With the US FDA recommending regular MRI screening of silicone breast implants, there is a need for a

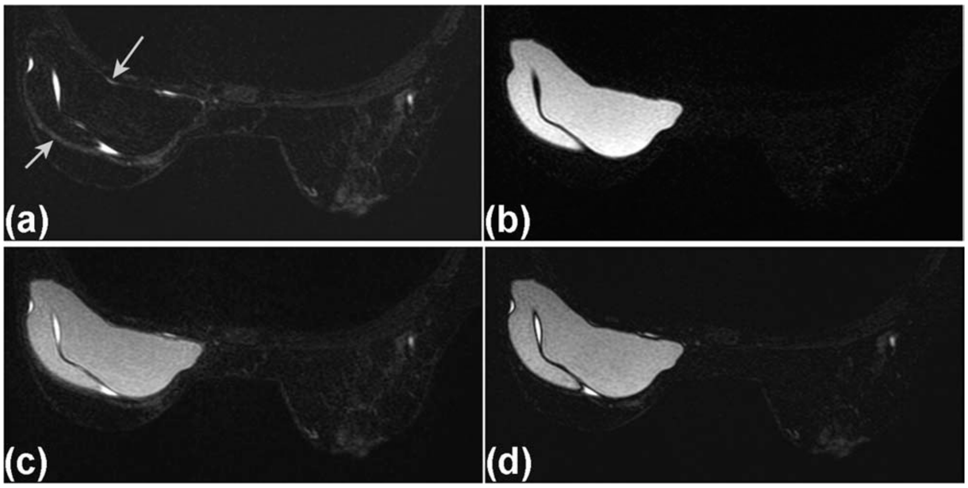

**Figure 2.** Uniformly separated water-only (a) and silicone-only (b) images of a 56-year-old normal volunteer with a unilateral breast implant. Using the water-only (**a**) and silicone-only (**b**) images, in-phase (**c**) and out-of-phase (**d**) images were generated. The intact fibrous capsule (arrows) is seen clearly on the water-only images. Image parameters were as follows: FOV = 300 × 300 $mm^2$, matrix = 320 × 224, slice thickness = 2 mm, spatial resolution = 0.9 × 1.3 × 2.0 $mm^3$, reconstructed to 0.6 × 0.6 × 1.0 $mm^3$, acquisition time = 10:00 min.

robust and rapid MR imaging technique to visualize silicone ruptures. In the current clinical practice, water-only and silicone-only images are often obtained in separate 2D acquisitions using various suppression strategies. Recently developed multipoint chemical shift-based techniques have enabled the reconstruction of water-only and silicone-only images in the same acquisition. However, these have been demonstrated only as 2D acquisitions, which require separate acquisitions in multiple orientations to capture and characterize abnormal findings. In this work, we have demonstrated near-isotropic, high spatial resolution volumetric $T_2$-weighted images of water and silicone with uniform separation and simultaneous fat suppression in a single acquisition. These images can be reformatted into any arbitrary plane, allowing several 2D acquisitions to be replaced with a single 3D acquisition that requires shorter overall scan time and facilitates visualization of implants from any orientation.

We compared the 3D acquisition against 2D-FSE-IDEAL with STIR, the latter being an investigational approach that has been shown to be more effective than traditional techniques (15). In contradistinction to using a single 3D acquisition, the 2D acquisitions had to be acquired in three separate orthogonal directions for a thorough evaluation of the implants. Additionally, the slice thickness with 2D acquisitions had to be increased to 6 mm with a slice gap of 1 mm for complete coverage of the implants in clinically feasible

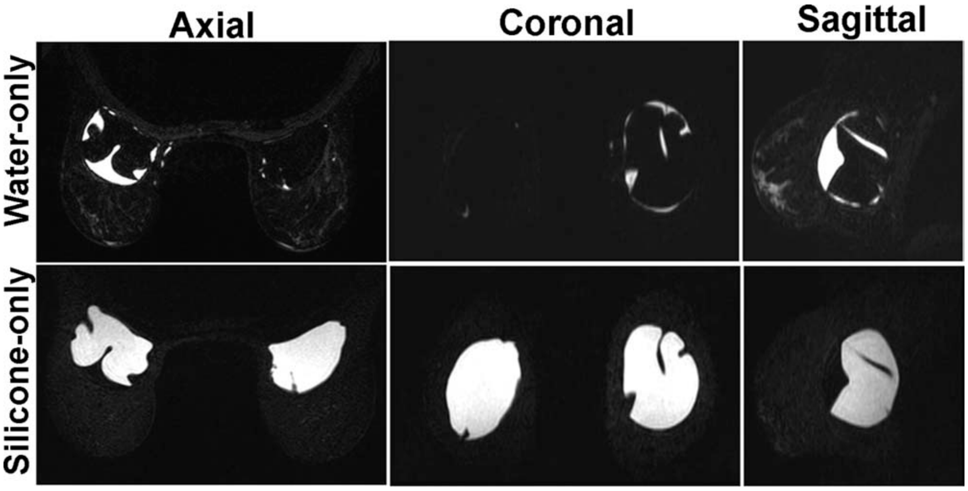

**Figure 3.** A double-lumen (saline-silicone) implant in the left breast and a single-lumen (silicone) implant in the right breast of a 62-year-old normal volunteer. The outer saline implant on the right is bright on the water-only image, while the inner silicone on the right and the silicone-only implant on the left are bright on the silicone-only image. Images were acquired in the axial plane and reformatted into coronal and sagittal orientations. Image parameters were as follows: FOV = 300 × 300 $mm^2$, matrix = 320 × 224, slice thickness = 2 mm, spatial resolution = 0.9 × 1.3 × 2.0 $mm^3$, reconstructed to 0.6 × 0.6 × 1.0 $mm^3$, acquisition time = 10:00 min.

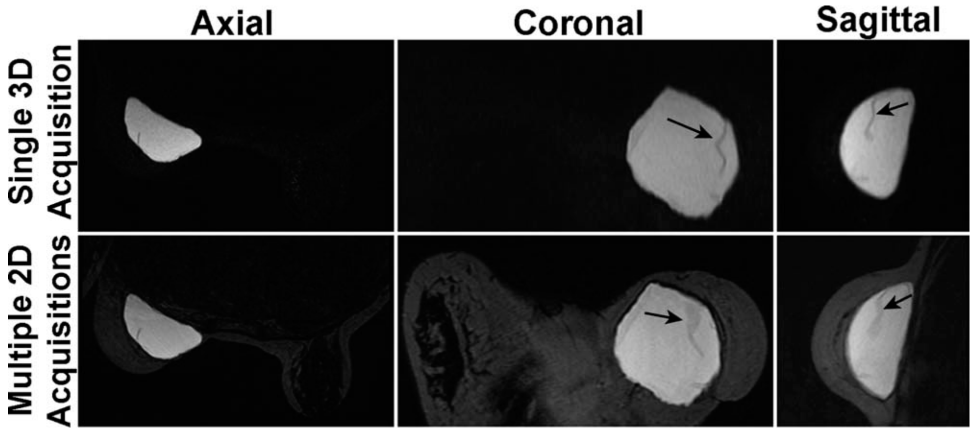

**Figure 4.** Top row: Silicone-only images of a 55-year-old normal volunteer from a single 3D acquisition. Images were acquired in the axial plane and reformatted into coronal and sagittal orientations. Bottom row: Silicone-only images from multiple 2D acquisitions. Similar slices are shown in both 3D and 2D acquisitions. Note the silicone folds clearly visible on the coronal and sagittal reformats of the 3D image, while the folds are less conspicuous on the 2D images due to partial volume (arrows). Fat appears bright on the 2D images due to a lower inversion time (120 ms) that was used with STIR. Image acquisition parameters were as follows: 3D acquisition—FOV = 270 × 270 $\text{mm}^2$, matrix = 288 × 224, slice thickness = 2 mm, spatial resolution = 0.9 × 1.2 × 2.0 $\text{mm}^3$, reconstructed to 0.5 × 0.5 × 1.0 $\text{mm}^3$, acquisition time = 7:02 min; 2D acquisitions—spatial resolution = 0.9 × 1.2 × 6.0 $\text{mm}^3$, reconstructed to 0.5 × 0.5 × 6.0 $\text{mm}^3$, acquisition times = 5:24 (axial), 4:38 (coronal), 4:04 (sagittal for each breast) min.

scan times. The scan times with 2D acquisitions could be further decreased with the use of parallel imaging, which was not used in this study. However, parallel imaging with 2D acquisitions is less effective as the acceleration can be performed along only one phase encoding direction, while they can be performed in both phase and slice encoding directions in a 3D acquisition.

Although the majority of the implants are single-lumen silicone implants, single-lumen saline implants as well as double-lumen implants containing both silicone and saline are also used. Because our technique generates both water-only and silicone-only volumetric images, these implants can be assessed using the single acquisition also, as demonstrated in Figure 3.

The scan times of the 3D acquisitions can be further decreased using various enhancements. One approach would be to acquire all IDEAL echoes in a single repetition, as previously demonstrated (30). These approaches, however, have certain limitations; for example, bipolar acquisition improves the time-efficiency of data collection but requires an additional phase correction (31). Alternatively, another approach would be to use higher parallel imaging acceleration factors facilitated by higher channel count coils (32), such as a 16-channel breast coil. The reduction in scan times could also be used to improve the spatial resolution along the slice encoding of the 3D acquisitions, which is currently inferior to the high in-plane resolution achieved with multi-planar 2D acquisitions.

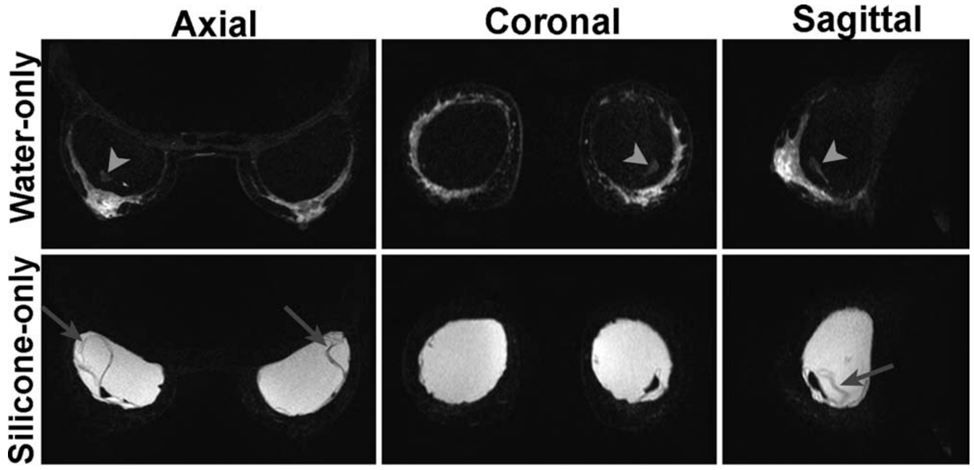

**Figure 5.** Water-only and silicone-only images of a 58-year-old volunteer, known to have bilateral intracapsular implant ruptures. Multiple curvilinear low signal intensity lines on the silicone-only images (arrows) are consistent with intracapsular rupture (linguine sign) resulting from the collapsed implant capsule floating in the silicone gel. No silicone was seen outside the fibrous capsule. Image acquisition parameters were as follows: FOV = 300 × 300 $\text{mm}^2$, matrix = 320 × 320, slice thickness = 2 mm, spatial resolution = 0.9 × 0.9 × 2.0 $\text{mm}^3$, reconstructed to 0.6 × 0.6 × 1.0 $\text{mm}^3$, acquisition time = 7:53 min.

However, the demands for spatial resolution may diminish with increased contrast resolution, depending on the application. Additionally, the scan time reduction can also be translated into increased slice coverage for potentially covering the lymph nodes, all in a single acquisition.

Recent studies have proposed using 3D $T_1$-weighted acquisitions with uniform water and silicone separation to reduce scan times (33–35). However, the long $T_1$ of silicone generates reduced signal intensity and silicone appears dark on $T_1$-weighted images. The long $T_1$ and $T_2$ favor the $T_2$-weighted contrast routinely used in current clinical evaluation. As demonstrated in our study, the single 3D $T_2$-weighted acquisition with uniform water and silicone separation can provide adequate information for the evaluation of breast implant integrity using a single acquisition. This finding needs to be further validated in a clinical setting.

In conclusion, we have demonstrated the utility of a robust fat-suppressed 3D $T_2$-weighted technique to acquire uniformly separated water and silicone images for rapid assessment of breast implants with a volumetric, high spatial resolution acquisition in a reasonable overall scan time. This single 3D acquisition allows the comprehensive assessment of breast implants in less than ten minutes.

## REFERENCES

1. Brown SL, Silverman BG, Berg WA. Rupture of silicone-gel breast implants: causes, sequelae, and diagnosis. Lancet 1997;350: 1531–1537.
2. Heden P, Bronz G, Elberg JJ, et al. Long-term safety and effectiveness of style 410 highly cohesive silicone breast implants. Aesthetic Plast Surg 2009;33:430–436; discussion 437–438.
3. Herborn CU, Marincek B, Erfmann D, et al. Breast augmentation and reconstructive surgery: MR imaging of implant rupture and malignancy. Eur Radiol 2002;12:2198–2206.
4. Holmich LR, Vejborg I, Conrad C, Sletting S, McLaughlin JK. The diagnosis of breast implant rupture: MRI findings compared with findings at explantation. Eur J Radiol 2005;53:213–225.
5. U.S. FDA (Nov. 17, 2006), FDA approves silicone gel-filled breast implants after in-depth evaluation. Available at: http://www.fda.gov/NewsEvents/Newsroom/PressAnnouncements/2006/ucm108790.htm. Accessed June 27, 2011.
6. Codner MA, Diego Mejia J, Locke MB, et al. 15 Year experience with primary breast augmentation. Plast Reconstr Surg 2011; 127:1300–1310.
7. Dorne L, Stroman P, Rolland C, et al. Magnetic resonance study of virgin and explanted silicone breast prostheses. Can proton relaxation times be used to monitor their biostability? ASAIO J 1994;40:M625–M631.
8. Mund DF, Farria DM, Gorczyca DP, et al. MR imaging of the breast in patients with silicone-gel implants: spectrum of findings. AJR Am J Roentgenol 1993;161:773–778.
9. Mukundan S Jr, Dixon WT, Kruse BD, Monticciolo DL, Nelson RC. MR imaging of silicone gel-filled breast implants in vivo with a method that visualizes silicone selectively. J Magn Reson Imaging 1993;3:713–717.
10. Monticciolo DL, Nelson RC, Dixon WT, Bostwick J III, Mukundan S, Hester TR. MR detection of leakage from silicone breast implants: value of a silicone-selective pulse sequence. AJR Am J Roentgenol 1994;163:51–56.
11. Gorczyca DP, Sinha S, Ahn CY, et al. Silicone breast implants in vivo: MR imaging. Radiology 1992;185:407–410.
12. Schneider E, Chan TW. Selective MR imaging of silicone with the three-point Dixon technique. Radiology 1993;187:89–93.
13. Gorczyca DP, Schneider E, DeBruhl ND, et al. Silicone breast implant rupture: comparison between three-point Dixon and fast spin-echo MR imaging. AJR Am J Roentgenol 1994;162:305–310.
14. Ma J, Choi H, Stafford RJ, Miller MJ. Silicone-specific imaging using an inversion-recovery-prepared fast three-point Dixon technique. J Magn Reson Imaging 2004;19:298–302.
15. O'Connell A-M, McKenzie CA, Madhuranthakam AJ, Pedrosa I, Dialani V, Rofsky NM. Faster magnetic resonance imaging of breast implants using the IDEAL technique. In: Proceedings of the 16th Annual Meeting of ISMRM, Toronto, 2008. (abstract 2724).
16. Alsop DC. The sensitivity of low flip angle RARE imaging. Magn Reson Med 1997;37:176–184.
17. Mugler JP, Kiefer B, Brookeman JR. Three-dimensional T2-weighted imaging of the brain using very long spin-echo trains. In: Proceedings of the 8th Annual Meeting of ISMRM, Denver, 2000. (abstract 687).
18. Hennig J, Weigel M, Scheffler K. Multiecho sequences with variable refocusing flip angles: optimization of signal behavior using smooth transitions between pseudo steady states (TRAPS). Magn Reson Med 2003;49:527–535.
19. Lichy MP, Wietek BM, Mugler JP III, et al. Magnetic resonance imaging of the body trunk using a single-slab, 3-dimensional, T2-weighted turbo-spin-echo sequence with high sampling efficiency (SPACE) for high spatial resolution imaging: initial clinical experiences. Invest Radiol 2005;40:754–760.
20. Busse RF, Hariharan H, Vu A, Brittain JH. Fast spin echo sequences with very long echo trains: design of variable refocusing flip angle schedules and generation of clinical T2 contrast. Magn Reson Med 2006;55:1030–1037.
21. Busse RF, Brau AC, Vu A, et al. Effects of refocusing flip angle modulation and view ordering in 3D fast spin echo. Magn Reson Med 2008;60:640–649.
22. Silver MS, Joseph RI, Hoult DI. Selective spin inversion in nuclear magnetic resonance and coherent optics through an exact solution of the Bloch-Riccati equation. Phys Rev A 1985;31:2753–2755.
23. Pineda AR, Reeder SB, Wen Z, Pelc NJ. Cramer-Rao bounds for three-point decomposition of water and fat. Magn Reson Med 2005;54:625–635.
24. Reeder SB, Yu H, Johnson JW, et al. T1- and T2-weighted fast spin-echo imaging of the brachial plexus and cervical spine with IDEAL water-fat separation. J Magn Reson Imaging 2006;24:825–832.
25. Reeder SB, McKenzie CA, Pineda AR, et al. Water-fat separation with IDEAL gradient-echo imaging. J Magn Reson Imaging 2007; 25:644–652.
26. Reeder SB, Pineda AR, Wen Z, et al. Iterative decomposition of water and fat with echo asymmetry and least-squares estimation (IDEAL): application with fast spin-echo imaging. Magn Reson Med 2005;54:636–644.
27. Hardy PA, Hinks RS, Tkach JA. Separation of fat and water in fast spin-echo MR imaging with the three-point Dixon technique. J Magn Reson Imaging 1995;5:181–185.
28. Madhuranthakam AJ, Yu H, Shimakawa A, et al. T2-weighted 3D fast spin echo imaging with water-fat separation in a single acquisition. J Magn Reson Imaging 2010;32:745–751.
29. Beatty PJ, Brau AC, Chang S, et al. A method for autocalibrating 2D accelerated volumetric parallel imaging with clinically practical reconstruction times. In: Proceedings of the 15th Annual Meeting of ISMRM, Berlin, 2007. (abstract 1749).
30. Li Z, Gmitro AF, Bilgin A, Altbach MI. Fast decomposition of water and lipid using a GRASE technique with the IDEAL algorithm. Magn Reson Med 2007;57:1047–1057.
31. Yu H, Shimakawa A, McKenzie CA, et al. Phase and amplitude correction for multi-echo water-fat separation with bipolar acquisitions. J Magn Reson Imaging 2010;31:1264–1271.
32. Giaquinto R, McKenzie CA, Sodickson DK, et al. A 28 channel bilateral breast array for accelerated MR imaging. In: Proceedings of the 14th Annual Meeting of ISMRM, Seattle, 2006. (abstract 423).
33. Po J, Margolis DJ, Cunningham CH, Herfkens RJ, Ikeda DM, Daniel BL. Water-selective spectral-spatial contrast-enhanced breast MRI for cancer detection in patients with extracapsular and injected free silicone. Magn Reson Imaging 2006;24:1363–1367.
34. Ma J. Silicone-specific imaging using a single-echo Dixon technique. In: Proceedings of the 16th Annual Meeting of ISMRM, Toronto, 2008. (abstract 2723).
35. Geppert C, Jellus V, Kiefer B. Three images from two echoes: reconstruction of water, fat and silicone images using a combined one-point and two-point Dixon approach. Application to 3D GRE in breast implant imaging. In: Proceedings of the 17th Annual Meeting of ISMRM, Honolulu, 2009. (abstract 2105).