Fully automated measurement of total adipose tissue volume using quantitative chemical shift MRI: Phantom Validation

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INTRODUCTION. Accurate identification and quantification of total adipose tissue (TAT) volume is a key first step for segmentation and measurement of visceral adipose tissue (VAT) and subcutaneous adipose tissue (SCAT), which are critical metrics in diagnosis and treatment of obesity-related diabetes, cardiovascular disease, and metabolic syndrome (1-3). Anthropometric measurements of waist circumference, waist-hip ratio, and body mass index (BMI) are widely used clinically to indirectly characterize TAT, VAT and SCAT, but are highly prone to systematic error (4-5) and correlate poorly with actual adipose tissue volumes (6-7). Qualitative segmentation using empirical signal thresholds and manual segmentation of adipose tissue on T1-weighted MRI is considered the reference standard for direct VAT measurement, but is prohibitively time-consuming for clinical use. Qualitative manual segmentation is also subject to partial volume effects at fat-water and fat-void interfaces, potentially leading to significant errors and poor repeatability in TAT/VAT/SCAT estimation. Chemical shift-based fat/water MRI methods are more accurate than T1-weighted MRI for visualizing adipose tissue (8-9) and potentially permit more rapid adipose tissue segmentation (10-11) by applying a simple fat-fraction threshold. However, the quantitative accuracy of chemical shift methods is confounded by relaxation effects (12-14) and spectral complexity of fat (13, 15), resulting in significant errors in fat-fraction values (16-17). Also, to avoid partial volume effects at signal boundaries, the fat-fraction threshold for adipose tissue is typically defined as 50%, implicitly assuming a maximum fat fraction (η_{MAX}) of 100%, but in vivo adipose tissue also contains organelles, blood vessels, and water components which result in a true $\eta_{MAX} < 100\%$. Therefore, $\eta_{MAX}/2$ is a more physiologically meaningful choice for adipose tissue thresholding, which can be directly measured from quantitative fat-fraction maps. ***The purpose of this work*** is to describe a quantitative chemical shift-based fat/water MRI method for fully automated estimation of η_{MAX} and volume of TAT. To assess the robustness of the TAT volume measurement with respect to partial volume effects, we employ a series of oil phantoms with varying volume and surface area complexity, using agar gel, glass rods, and empty plastic vials.

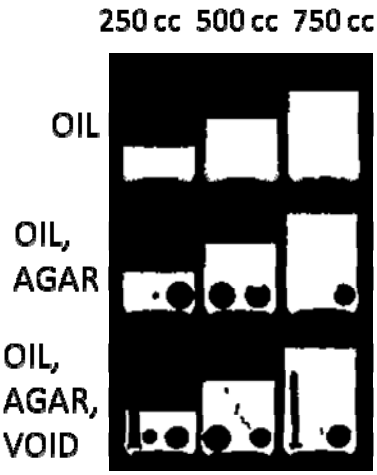

FIGURE 1. Noise-masked fat-fraction maps for each oil phantom of varying volume and surface area complexity. The fat-fraction values are nearly unity in oil and nearly zero in agar and the signal void regions of air and glass.

METHODS. A phantom comprised of nine bottles of peanut oil, with varying oil volumes (250 cc, 500 cc, and 750 cc) and increasing surface area complexity (oil, oil with 2% agar spheres, and oil with 2% agar spheres, glass rods, and air cavities) was constructed to test the performance of the TAT estimation algorithm (Figure 1). MR images were acquired on a clinical 3.0 T MRI scanner (GE Healthcare, Waukesha WI) using a 32-channel phased-array body coil (Neocoil, Pewaukee WI). The acquisition used a single-slab 3D multi-echo spoiled gradient-echo (SPGR) pulse sequence (18) with 6 echoes/TR and 1.2 ms echo spacing (13, 15), and flip angle of 3^O to minimize T1-weighting bias (12). Data was acquired in the sagittal plane with 44.8 cm FOV, 148 x 148 matrix and 160 slices of 2 mm, interpolated to 1.75 x 1.75 x 1.0 mm^3. Auto-calibrated parallel imaging (ARC) (19) accelerated the acquisition by a factor of 5.32, for total scan time of 26 sec. Fat and water images were reconstructed offline and used to generate quantitative fat-fraction maps with full dynamic range of 0-100% (12). A custom thresholding algorithm was then applied to fat and water data to automatically suppress background noise and signal voids from glass and air cavities. The maximum fat-fraction value η_{MAX} was estimated using histogram analysis, with identical value in all bottles of 0.98 ± 0.0 An "adipose mask" was then defined as all voxels of the noise-masked fat-fraction map with values greater than or equal to $\eta_{MAX}/2$. The TAT volume was then obtained by multiplying the number of voxels in the adipose tissue mask by the single-voxel volume. Total processing time of raw fat and water data to TAT volume was < 5 min and required no user intervention.

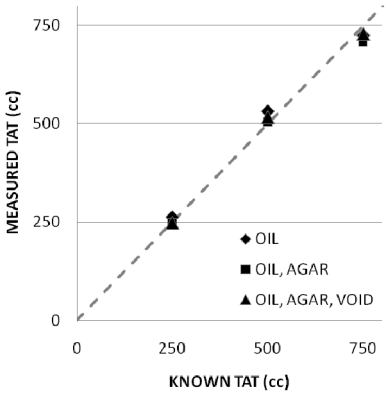

FIGURE 2. The TAT volumes measured by the fully automatic algorithm are highly accurate, and robust despite increasing partial volume effects; r^2 = 0.991, 0.995, and 0.996 for OIL, OIL+AGAR, and OIL+AGAR+VOID, respectively.

RESULTS. The automated algorithm accurately measured TAT volume in each phantom, with maximum error under 3% of the known volume of oil ($p > 0.44$). The accuracy of the algorithm was unaffected by increasing surface area of fat-water and fat-void boundaries (Figure 2).

DISCUSSION. The automated TAT algorithm was immune to partial volume effects, providing highly accurate measurements of TAT even at the higher levels of surface area complexity.

REFERENCES. [1] Alberti KG, Lancet. 2005;366:1059. [2] Bergman RN, Obesity. 2006;14:16S. [3] Despres JP, Nature. 2006;444:881. [4] Agarwal SK, Obesity. 2009;17:1056. [5] Mason C, Obesity. 2009;17:1789. [6] Joy T, Metabolism. 2009;58:828. [7] Ludescher B, Invest Radiol. 2009;44:712. [8] Bley TA, JMRI. 2010;31:4. [9] Bornert P, JMRI. 2007;25:660. [10] Alabousi A. Proc ISMRM. 2009;17:2880. [11] Kullberg J, JMRI. 2009;30:185. [12] Liu CY, MRM. 2007;58:354. [13] Yu H, JMRI. 2007;26:1153. [14] Bydder M, MRI. 2008;26:347. [15] Yu H, MRM. 2008;60:1122. [16] Kim H, MRM. 2008;59:521. [17] Reeder SB, JMRI. 2009;29:1332. [18] Reeder SB, JMRI. 2007;25:644. [19] Brau AC, MRM. 2008;59:382.

Acknowledgments: This work was supported by the NIH (R01 DK083380, R01 DK088925 and RC1 EB010384), the Coulter Foundation, and GE Healthcare.