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 ($\eta_{\text{MAX}}$) of 100%, but in vivo adipose tissue also contains organelles, blood vessels, and water components which result in a true $\eta_{\text{MAX}}$ < 100%. Therefore, $\eta_{\text{MAX}}$/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 $\eta_{\text{MAX}}$ 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.

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 (Neocoi, 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 $\pi$ 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 mm3. 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 $\eta_{\text{MAX}}$ 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 $\eta_{\text{MAX}}$/2. The TAT volume was then obtained by multiplying the number of voxels in the adipose tissue mask 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 $\eta_{\text{MAX}}$ 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 $\eta_{\text{MAX}}$/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.

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.


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