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Whole-body Continuously Moving Table Fat-Water MRI with Dynamic B_0 Shimming at 3 Tesla

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Abstract

Purpose—The purpose of this work was to develop a rapid and robust whole-body fat-water magnetic resonance imaging (FWMRI) method using a continuously moving table (CMT) with dynamic field corrections at 3 Tesla.

Methods—CMT FWMRI was developed at 3 Tesla with a multi-echo golden angle (GA) radial trajectory and dynamic B_0 field shimming. Whole-body imaging was performed with 4 echoes and superior-inferior coverage of 1.8 meters without shims in 90 seconds. 716 axial images were reconstructed with GA profile binning followed by B_0 field map generation using fast three-point seeded region growing fat-water separation and slice-specific 0th and 1st order shim calculation. Slice-specific shims were applied dynamically in a repeated CMT FWMRI scan in the same session. The resulting images were evaluated for field homogeneity improvements and quality of fat-water separation with a whole-image energy optimized algorithm.

Results—GA sampling allowed high quality whole-body FWMRI from multi-echo CMT data. Dynamic B_0 shimming greatly improved field homogeneity in the body and produced high quality water and fat only images as well as fat signal fraction and R_2^* relaxivity maps.

Conclusion—A rapid and robust technique for whole-body fat-water quantification has been developed with CMT MRI with dynamic B_0 field correction.

Keywords

Continuously moving table MRI; Fat-water MRI; Golden angle radial Dynamic B_0 Shimming

INTRODUCTION

The mapping and quantification of whole-body fat and water content is valuable in the staging and treatment of disorders linked to obesity, diabetes and liver disease (1). Fat-water magnetic resonance imaging (FWMRI) based on multi-echo gradient echo MRI is a noninvasive technique that can provide accurate, clinically relevant whole-body measurements of fat and water fractions, without the need for ionizing radiation (2). In addition to visualizing the location of adipose tissue, modern quantitative FWMRI techniques also provide a detailed mapping of the ectopic distribution of fat in non-adipose tissues such as skeletal muscle and the liver.

Whole-body fat-water MRI has traditionally been performed with multi-station scanning in which the extended z direction field of view (zFOV) is scanned in multiple sections (1). This approach is time consuming and prone to data inconsistency errors between imaged sections. A promising alternative uses a continuously moving table (CMT) for data acquisition. CMT MRI enables very efficient scanning of the whole-body with minimal patient discomfort and has been explored for many applications, including multi-contrast anatomical imaging (3–5), peripheral vascular angiography (6,7), oncology (8), as well as whole-body FWMRI (9–11).

One of the challenges with CMT based FWMRI is that, in general, the table motion imposes trade-offs between z resolution (Δz), table velocity (v) and repetition time (TR). For a single slice radial CMT MRI scan, the reconstructed image slice thickness is given by

$$\Delta z = v * TR * N \quad (1)$$

where N is the number of projections in a full 180° sampled acquisition (12). For FWMRI, multiple echoes are needed to sample the water and fat phase evolutions at different time points following excitation. With multiple echoes per TR , and hence longer minimum TR s, the nominal reconstructed slice thickness is increased leading to loss of resolution in the z direction. Recently, a method for CMT MRI was presented based on golden angle (GA) radial sampling to overcome this limitation (13). GA sampling allows retrospective profile binning for arbitrary slice thickness reconstructions and high degrees of radial under-sampling without coherent artifacts in the reconstructed image. This technique allows the recovery of slice resolution in the z direction, and is therefore ideally suited for the multiecho acquisitions needed in FWMRI.

Another limitation of traditional CMT FWMRI methods is that unlike multi-station scanning approaches, the center-frequency (F_0) and shim calibrations are performed at one location of the body (commonly, the abdomen) and maintained for the full field of view. This results in non-optimal and often damaging off-resonance (B_0) field compensation in other sections of the body. As an alternative, the shims may be entirely deactivated to avoid extreme fields. However, forgoing shimming wastes the opportunity to correct field inhomogeneities that often prove deleterious in FWMRI. Poor B_0 homogeneity causes inaccurate fat-water separation, especially in locations where B_0 is extreme such as the neck, shoulders and upper abdomen (10).

The purpose of this work was therefore twofold. The first goal was to develop CMT FWMRI based on GA radial sampling at 3 Tesla. GA sampling relaxes the limits on slice thickness imposed by the table speed and allows the collection of a higher number of echoes per TR for accurate fat-water separation, as well as whole-body B_0 mapping. The second goal was to present a proof of concept solution to correct whole-body field inhomogeneity by dynamically shimming different positions of the moving table during a CMT scan with shim settings optimal for each individual slice. This is accomplished in a two step scan where the unshimmed whole-body B_0 is measured in an initial scan and derived slice-wise shims are applied in a second dynamically shimmed scan in the same scan session. This leads to greatly improved whole-body field homogeneity and high quality fat and water images.

METHODS

CMT MRI setup

CMT FWMRI was implemented on a Philips Achieva 3 Tesla scanner (Philips Healthcare, Best, The Netherlands) with a 2-channel transmit/receive body coil and no surface coil. Software modifications enabled table motion during a scan with a speed of 20 mm/s. No hardware changes were performed for this setup. CMT FWMRI was implemented as a continuous, single-slice axial radial scan with the total number of profiles (N) derived from Eqn. 1 for the zFOV. The subject's umbilicus was landmarked and placed at isocenter during scan preparation phases to set a center frequency and RF power level. After the completion of scan preparation phases, the table moved to the fully extended position. Scanning was performed continuously using the integrated quadrature body coil in two-channel transmit and receive mode. To maximize z sampling, the scanner's full control gradient mode was utilized, which allowed maximum gradient strengths and slew rates of 40 mT/m and 200 mT/m/s respectively. The radial profiles were stepped azimuthally by 111.246 degrees for GA radial imaging (13,14).

Human data acquisition and Initial field mapping

Two adult volunteers, one female (weight 73 kg, height 175 cm, Body mass index BMI 23.7) and one male (weight 86 kg, height 170 cm, BMI 29.8) were scanned with informed IRB consent at 3 Tesla. A single slice GA radial CMT scan was performed first with 4 echoes and the following imaging parameters: zFOV = 1800 mm, in-plane FOV = 400×400 mm², in-plane resolution = 2.5×2.5 mm², TR = 6.6 ms, first TE/ TE = 0.99/1.4 ms, excited slice thickness = 12 mm 13,792 total radial profiles with flyback gradients and a total acquisition time of 90 seconds. All the shims were initially set to zero to maintain a globally acceptable shim setting. Following the scan, data reconstruction, fat-water separation with whole-body B_0 estimation and slice-specific 0th and 1st order B_0 shim calculations were performed as described in the following sections to produce 716 slice-specific shims along the full extent of the body. The multi-echo CMT scan was then repeated in the same session with the shim settings updated continuously for dynamically shimmed FWMRI.

Image Reconstruction at the Scanner

Complex images were reconstructed at the scanner on a network-connected laptop immediately following the unshimmed CMT scan using a custom code written in the Julia

programming language (Julia v0.3.4, MA, USA, <http://julialang.org>) (15). Slices were reconstructed with slice centers separated by 2.5 mm, matching the $2.5 \times 2.5 \text{ mm}^2$ in-plane resolution. 128 GA profiles were included per slice, covering a nominal slice of thickness 16.9 mm ($128 * 6.6 \text{ ms} * 20 \text{ mm/s}$). The reconstruction resulted in 716 slices per TE over the 1.8 m zFOV. The image reconstruction pipeline has been described in detail earlier (13). Briefly, 128 profiles per slice were collated, corrected for k space shifts and pre-weighted for sampling density correction. The pre-weighted data were gridded slice-by-slice with a Kaiser-Bessel kernel, transformed using a 2D FFT and then roll-off corrected using the same kernel (13).

Fat-Water separation and fieldmap generation

The complex multi-echo whole-body images were used for generating fat-water volumes and a B_0 fieldmap. A MATLAB (Mathworks, MA, USA) implementation of a three-point multi-seeded region-growing algorithm proposed by Berglund et al (11) was used for the fat-water separation. Only the first three echoes were included in the separation algorithm. The individual echo images were masked using Otsu's thresholding method based on the echo 1 magnitude image. The signal model included nine fat resonances with chemical shifts and relative amplitudes reported in a liver spectroscopy study of 121 human subjects (16). The separation algorithm produced a 716-slice B_0 field map of the whole-body.

Estimation and application of slice specific shims in FWMRI scan

Slice specific 0th (F_0 in Hz) and 1st order (X, Y, Z in mTesla/m) shims were calculated in MATLAB for all 716 slices using the whole-body unshimmed B_0 field map. To calculate shims for a particular slice, field maps for that slice and two slices on either side were fit for a constant offset frequency and linear shim coefficients (17). Since the initial fieldmap was produced from an unshimmed volume, there were locations of extreme field inhomogeneity that exhibited field wraps, particularly in the chest, arms and shoulders. These wraps could introduce errors in the shim calculations. To address this problem, a hard threshold of ± 350 Hz was introduced in addition to the magnitude mask (TE was 1.4 ms, i.e. 357 Hz for a field wrap of $> \pi$ radians) to mask the fieldmaps prior to shim estimation. The 716 unique F_0 , X, Y and Z shim values were spline interpolated to 13,792 values, one for each of the radial projections in the CMT scan. Therefore, a distinct shim set was generated for every 0.132 mm of superior-inferior anatomical separation. The shim values were exported to the scanner as a text file to be available for subsequent scans. The scanner software was modified to load the shims from the text file and to enable dynamic switching of the shims every TR. The multi-echo CMT scan was repeated with dynamic shimming activated where the 0th order correction was applied via a center frequency adjustment and the 1st order shims were adjusted using the linear gradient offsets prior to slice excitation.

Computational time

Computational time was critical since performing a dynamically shimmed scan requires that the entire process of reconstructing multi-echo whole-body images, generating fieldmaps via fat-water separation, and estimating slice-specific shims be accomplished within a time duration that permits dynamic shimming in the same scan session. The use of a multithreaded Julia implementation for image reconstruction enabled each individual $160 \times$

160 × 716 matrix echo volume to be reconstructed in approximately 100 seconds. In comparison, an equivalent Python (Anaconda version 3.4.2, Continuum Analytics, Austin, TX) implementation reported earlier required approximately 25 minutes per echo on the same laptop computer (2.66 GHz Intel Core I7, 8 GB RAM) (13). Fat-water separation and field map generation took 200 seconds and shim estimations took another approximately 500 seconds (both in MATLAB 2014b). In total, the entire scan-to-scan time was 1100 seconds (18 minutes 20 seconds), which made proof-of-concept dynamically shimmed fat-water MRI experiment possible in the same scan session.

Retrospective Image Reconstruction and Fat-Water Separation

After the scan session, whole-body data sets were reconstructed from both unshimmed and dynamically shimmed data in Python. The reconstruction steps have been presented in detail earlier (13). Since processing time was not a constraint in the retrospective setting, a slower but more robust algorithm based on whole-image optimization presented by Berglund and Kullberg, (18) was employed for fat-water separation. The algorithm used all four acquired echoes to estimate whole-body water, fat, B_0 and R_2^* (constrained to 120 s⁻¹) images. The fat-water maps were visually inspected for species swaps. A whole-body fat signal fraction (FSF) map was generated as $1 - |W|/(|F| + |W|)$ where $|F|$ and $|W|$ were the fat and water magnitude images respectively. Slice-wise signal intensities for water and fat were also estimated as magnitude projections for both species.

RESULTS

Figure 1 shows whole-body coronal reformatted images from the dynamically shimmed multi-echo scan, echoes 1 through 4 (Python reconstructions) for the female subject. High image quality is obtained with the GA CMT technique even with the relatively high table speed of 20 mm/s. The fat-water phase modulations are apparent in the contrast variation over the four echoes. As expected, the signal-to-noise ratio (SNR) degrades with echo time, and the decay is most pronounced in locations where field homogeneity is typically the most severe, i.e. the edges of the field of view, the shoulders and the upper abdomen.

Coronal and sagittal views in Figures 2a,d and 2c,f demonstrate the effect of dynamic 0th and 1st order B_0 field corrections in the X (anterior-posterior), Y (left-right) and Z (head-foot) axes, with the corresponding 716 × 4 (X, Y, Z and F0) slice-specific shim values shown in Figures 2b and 2e for the two subjects. Significant improvement is observed in the field homogeneity in multiple regions of the body for both subjects, with maximum improvements seen in the brain, neck, shoulders and abdomen. Shims vary significantly in amplitude and sign in the different sections of the body. The Z, X and F0 components have peak-to-peak values of 0.188 mT/m, 0.178 mT/m and 418 Hz respectively for subject 1 and 0.193 mT/m, 0.151 mT/m and 387 Hz respectively for subject 2. The maximum absolute corrections for Z, X and F0 are observed in the shoulder, neck and head respectively. The Y component does not show significant variation with slice location (0.03 mT/m peak-to-peak and subject 1 and 0.04 mT/m for subject 2), which reflects the general left-right symmetry of the unshimmed field. Higher order residual field variations are also observed in several locations along the body. Some of these residual variations may be addressed with higher

order shimming, but many of them may be beyond the harmonic range of typical scanner shim systems.

Figure 3 shows results of retrospective fat-water separation performed on the dynamically shimmed image volume for the female subject. Figure 3a shows whole-body single slice coronal images, depicting in detail the distribution of each species in the body. The quality of fat-water separation is consistently high across the body, with no obvious fat-water swaps. Figure 3b shows axial slices across the head, shoulders, thorax, lower abdomen, thighs and knees illustrating the high anatomical detail and accurate fat-water separations produced.

Figure 4 shows results of retrospective fat-water separation performed on the dynamically shimmed image volume for the male subject with BMI of 29.8. While the coronal view in Figure 4a does not indicate large adipose tissue depots, the high BMI may be understood from the sagittal view in Figure 4b where significant fat deposition is observed around the visceral organs in the abdomen. This is also reflected in the axial slice across the abdomen in Figure 4c.

Whole-body dynamically shimmed FSF and R_2^* maps are shown in Figures 5a and 5c. High R_2^* values are seen in the locations of the neck, shoulders, heart and the upper abdomen and ankles as expected. The FSF map shows normalized fat signal fraction in the whole-body. Figure 5b shows slice-wise fat and water signal projections for the whole body depicting the fat and water signal contributions in each slice.

DISCUSSION

This study describes a rapid and robust technique for whole-body FWMRI with dynamically shimmed CMT at 3 Tesla. Whole-body multi-echo CMT MRI images are acquired with a GA radial trajectory in only 90 seconds. Significant improvements in whole-body field homogeneity are demonstrated with dynamic 0th and 1st order shimming. High quality whole-body fat-water images, fat signal fraction maps and R_2^* maps are also generated.

The use of the GA strategy in radial CMT MRI is a key aspect of this study. In linear angle CMT MRI, the table speed, TR and radial profile density impose limits on the minimum slice thickness. Also, these parameters have to be prescribed a-priori to avoid image reconstruction artifacts. A GA acquisition is independent of the desired reconstructed slice thickness. This allows the acquisition of multiple echoes with extended repetition times without constraining the reconstructed slice thickness.

The significant variations of the B_0 field along the body observed in the un-shimmed image clearly demonstrate the need for slice-specific shimming. Dynamic B_0 shimming will be key to improving image quality in multiple CMT applications that rely on steady-state conditions or low bandwidth readouts, such as whole-body diffusion weighted imaging, that are prone to B_0 artifacts. The fieldmaps generated by the 20mm/s table speed scans in this study are observed to smoothly vary in general. It may therefore be possible to employ a faster table speed fieldmapping scan at a lower resolution to further accelerate the imaging, without major errors in the shims. A limitation of this work was the restriction of dynamic corrections to the first order. Higher order corrections can further improve field

homogeneity, with particular gains in the left-right field, which presents 2nd order field symmetry. However, implementation of higher order dynamic shimming is challenging due to scanner hardware limitations and eddy currents produced from rapid shim current switching (17).

Rapid computation time was a primary emphasis in this study, since dynamic shimming is a multistep process. The multi-threaded implementation in Julia enabled this process to be accomplished within 18 minutes for the $160 \times 160 \times 716 \times 4$ matrix volume. Future work will focus on reducing the computation time further with Julia implementations of the fat-water separation algorithm and shim calculations for completely inline data processing.

The quality of the whole-body fat and water images produced by the dynamically shimmed CMT technique was consistently high across the body. Several FWMRI studies have employed a higher number of echoes for fat/water separation (19). In this work, we used 4 echoes in order to increase the z direction sampling. While increasing the number of echoes may be beneficial for fat-water separation, the increased TRs may on the other hand reduce image quality with more partial volume effects in the reconstructed axial slices. Also, we have employed 9-peak fat model for our separation algorithm in this work. While this yields high quality fat/water images, simpler, lower peak number models may be sufficiently robust for good fat/water separation, with the 4-echo based acquisition. A limitation of this study was that the images were only visually inspected for swaps without expert evaluation by a radiologist. Qualitatively, no significant errors were observed in the separation results. The goal of this preliminary proof-of-concept study was limited to the initial development of dynamically shimmed multi-echo CMT FWMRI, and demonstration of fat-water separation using the technique. Also, quantitative evaluation was limited to estimation of FSF maps and slice-wise fat and water signal projection measurements. Validation of these measurements by MR spectroscopy or biopsy was beyond the scope of this study. The segmentation and quantification of visceral versus subcutaneous adipose tissue is also of high interest in the study of obesity. Algorithms for automated segmentation of visceral adipose tissue have been presented by others and will be the subject of future investigation with GA CMT based FWMRI (9).

The benefit of dynamic shimming may be most realized in FWMRI (and other B_0 sensitive imaging sequences) of obese subjects, where significantly higher field inhomogeneities are expected. In this study, the TE of 1.4 ms for 2.5 mm resolution readouts allowed a spectral bandwidth of ± 357 Hz (± 2.79 ppm). This relatively large bandwidth minimized wraps in the B_0 field (Figure 2a,d), leading to robust fat-water separations for both unshimmed and dynamically shimmed cases. For larger fields of view for obese subjects or higher image resolutions, increased TEs will lead to lower spectral bandwidths, more frequent field wraps and error prone fat-water separations. Dynamic shimming promises to be a powerful technique for overall image quality improvements for such cases.

In support MRM's mission of reproducible research we plan to share our source code and data with the community once the article has been accepted for publication. The material will be freely available at https://github.com/senguptasaikat/MRM_Sengupta_Moving_Table_Dynamic_Shim_Fat_Water_MRI

CONCLUSION

A technique has been developed for rapid whole-body FWMRI with a continuously moving table at 3 Tesla. A multi-echo golden angle radial scan has been developed to image an extended field of view of 1800 mm covering an adult human whole body in 90 seconds. In addition, we have presented a dynamic slice-specific shimming technique that improves B_0 field homogeneity in all the sections of the body. High quality fat and water images are generated, along with whole-body maps of R_2^* and fat signal fraction.

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References

1. Brennan DD, Whelan PF, Robinson K, Ghita O, O'Brien JM, Sadleir R, Eustace SJ. Rapid automated measurement of body fat distribution from whole-body MRI. *AJR Am J Roentgenol*. 2005; 185:418–23. [PubMed: 16037514]
2. Hu HH, Kan HE. Quantitative proton MR techniques for measuring fat. *NMR Biomed*. 2013 Dec; 26(12):1609–29. Epub 2013 Oct 3. [PubMed: 24123229]
3. Börnert P, Aldefeld B. Principles of whole-body continuously-moving-table MRI. *J Magn Reson Imaging*. 2008; 28:1–12. [PubMed: 18581358]
4. Barkhausen J, Quick HH, Lauenstein T, Goyen M, Ruehm SG, Laub G, Debatin JF, Ladd ME. Whole-body MR imaging in 30 seconds with real-time true FISP and a continuously rolling table platform: feasibility study. *Radiology*. 2001; 220:252–6. [PubMed: 11426006]
5. Johnson KM, Leavitt GD, Kayser HW. Total-body MR imaging in as little as 18 seconds. *Radiology*. 1997; 202:262–7. [PubMed: 8988221]
6. Kruger DG, Riederer SJ, Grimm RC, Rossman PJ. Continuously moving table data acquisition method for long FOV contrast-enhanced MRA and whole-body MRI. *Magn Reson Med*. 2002; 47:224–31. [PubMed: 11810664]
7. Madhuranthakam AJ, Kruger DG, Riederer SJ, Glockner JF, Hu HH. Time-resolved 3D contrast-enhanced MRA of an extended FOV using continuous table motion. *Magn Reson Med*. 2004; 51:568–76. [PubMed: 15004799]
8. Schaefer AO, Langer M, Baumann T. Continuously moving table MRI in oncology. *Rofo*. 2010; 182:954–64. [PubMed: 20922644]
9. Kullberg J, Johansson L, Ahlström H, Courivaud F, Koken P, Eggers H, Börnert P. Automated assessment of whole-body adipose tissue depots from continuously moving bed MRI: a feasibility study. *J Magn Reson Imaging*. 2009 Jul; 30(1):185–93. [PubMed: 19557740]
10. Börnert P, Keupp J, Eggers H, Aldefeld B. Whole-body 3D water/fat resolved continuously moving table imaging. *J Magn Reson Imaging*. 2007; 25:660–5. [PubMed: 17326078]
11. Berglund J, Johansson L, Ahlström H, Kullberg J. Three-point Dixon method enables whole-body water and fat imaging of obese subjects. *Magn Reson Med*. 2010 Jun; 63(6):1659–68. [PubMed: 20512869]
12. Shankaranarayanan A, Herfkens R, Hargreaves BM, Polzin JA, Santos JM, Brittain JH. Helical MR: continuously moving table axial imaging with radial acquisitions. *Magn Reson Med*. 2003; 50:1053–60. [PubMed: 14587016]
13. Sengupta S, Smith DS, Welch EB. Continuously moving table MRI with golden angle radial sampling. *Magn Reson Med*. 2014 Dec 2. [Epub ahead of print].
14. Winkelmann S, Schaeffter T, Koehler T, Eggers H, Doessel O. An optimal radial profile order based on the Golden Ratio for time-resolved MRI. *IEEE Trans Med Imaging*. 2007; 26:68–76. [PubMed: 17243585]

15. Bezanson J, Chen J, Karpinski S, Shah V, Edelman A. Array operators using multiple dispatch: A design methodology for array implementations in dynamic languages. ARRAY'14 Proceedings of ACM SIGPLAN International Workshop on Libraries, Languages, and Compilers for Array Programming. 2014:56–61.
16. Hamilton G, Yokoo T, Bydder M, Cruite I, Schroeder ME, Sirlin CB, Middleton MS. In vivo characterization of the liver fat ¹H MR spectrum. NMR Biomed. 2011 Aug; 24(7):784–90. [PubMed: 21834002]
17. Sengupta S, Welch EB, Zhao Y, Foxall D, Starewicz P, Anderson AW, Gore JC, Avison MJ. Dynamic B0 shimming at 7 T. Magn Reson Imaging. 2011 May; 29(4):483–96. Epub 2011 Mar 12. [PubMed: 21398062]
18. Berglund J, Kullberg J. Three-dimensional water/fat separation and T2* estimation based on whole-image optimization--application in breathhold liver imaging at 1.5 T. Magn Reson Med. 2012 Jun; 67(6):1684–93. Epub 2011 Dec 21. [PubMed: 22189760]
19. Hu HH1, Kan HE. Quantitative proton MR techniques for measuring fat. NMR Biomed. 2013 Dec; 26(12):1609–29. [PubMed: 24123229]

Figure 1.

Whole-body coronal reformatted images from the four echoes at TEs 0.99, 2.39, 3.79 and 5.19 ms. Fat-water contrast varies with TE, as expected. The SNR degrades with increasing echo time, with most signal decay observed in locations of high field inhomogeneity both due to tissue susceptibility differences (neck, shoulders) as well as field of view edge effects (arms, hips). Some image artifacts and signal losses associated with abdominal motion of the subject are observed in the liver (short arrow, 1d). The arrow in 1a shows the direction of table motion.

Figure 2.

Results of whole-body CMT dynamic shimming: (a–c) subject 1 and (d–f) subject 2 (a) Masked coronal field map showing improvements in B_0 homogeneity across the whole body with dynamic shimming. Largest improvements are observed in the neck, shoulders, upper abdomen, hips and knees. (b) X, Y, Z and F0 shim values in mTesla/m (top axis) and Hz (bottom axis) optimized for 716 axial slices in the body. The Z (head-foot), X (anterior-posterior) and F0 components show significant variations in amplitude and sign, with peak-to-peak values of 0.188 mT/m, 0.178 mT/m and 418 Hz. The Y component does not show

large variations (0.03 mT/m peak-to-peak), which is reflective of the general symmetry of the field in the left-right direction. (c) A sagittal view of the field map in the same scale as 2a illustrating field improvements in the anterior-posterior direction. (d) coronal fieldmaps for subject 2 (e) Shim corrections and (f) sagittal fieldmaps.

Figure 3.

Water only and fat only whole-body images with dynamic B_0 shimming. (a) Coronal water and fat image slices showing the distribution of the chemical species. High anatomical detail is observed with clear mapping of subcutaneous and visceral fat depots. Some image artifacts associated with abdominal motion of the subject are observed in the liver, with a slight fat-water swap in the dome of the liver. (b) Water and fat axial slices in 6 different locations of the body: the brain, shoulders, thorax, lower abdomen, thighs and knees. Excellent fat-water separation is observed in all locations. The arrow in 3a shows the direction of table motion. The volunteer had a wire implant in the sternum that produced an artifact apparent in the chest axial slice.

Figure 4. Water and fat only whole-body images with dynamic B_0 shimming for subject 2. (a) Coronal slices showing the distribution of the chemical species. (b) Sagittal slice showing significant adipose tissue depots in the abdomen (c) Axial slice across the abdomen illustrating large visceral adipose tissue volume.

Figure 5.

(a) Whole-body FSF map showing voxel-wise fat fraction (b) Whole body slice-wise fat and water signal fractions, showing the distributions of the two species in different locations of the body calculated as the summed slicewise signal intensities for each species. (c) whole-body R_2^* map in s^{-1} .