Optimization of Fat-Water Separation Algorithm Selection and Options Using Image-Based Metrics with Validation by ISMRM Fat-Water Challenge Datasets

***David S. Smith*[1,2], *Johan Berglund*[3], *Joel Kullberg*[4], *Håkan Ahlström*[4], *Malcolm J. Avison*[1,2,5], *E. Brian Welch*[1,2]**

[1]Vanderbilt University Institute of Imaging Science (VUIIS), [2]Department of Radiology and Radiological Sciences,
[3]Philips Healthcare, Stockholm, Sweden, [4]Department of Radiology, Uppsala University Hospital, Uppsala, Sweden,
[5]Department of Pharmacology, [1,2,5]Vanderbilt University School of Medicine, Nashville Tennessee

#2413

PURPOSE

The objective of this research is to develop and describe a robust fat-water separation algorithm for multi-echo MRI that is applicable to datasets spanning a wide range of anatomy, magnetic field strengths and collected echo times. The algorithm is validated in the context of the 2012 ISMRM Fat Water Challenge [1]. Our team (Fatty Riot) is one of seven teams participating in Phase II of the challenge. The winning team will be announced on Thursday morning (April 25, 2013) after the Young Investigator Award presentation (08:00 Plenary Hall). In the blinded Phase II of the competition, it was not possible to manually tweak algorithms to produce better results. At the time of submission for ISMRM 2013 abstracts, we believed our final entry would contain logic to predict the best (or nearly best) option among multiple available results.

In this poster, we outline an embodiment of such a metric-based selection algorithm with the disclaimer that our algorithm evolved over the months since abstract submission to a point where no image-based metrics were used. We also describe the steps of our final algorithm as it was submitted in the Phase II of the challenge.

MATERIALS AND METHODS

Fatty Riot was registered as an ISMRM Challenge team with member names matching the coauthors of this abstract. The 10 test cases were downloaded and processed with code run in MATLAB R2010a and C++ accessible via a MATLAB wrapper function. Algorithms [2-9] available in the ISMRM Fat-Water Toolbox [10] were selected for evaluation. We also applied an algorithm currently not available in v1.0 of the Fat-Water ISMRM toolbox that uses a whole-image energy cost function minimization approach [11].

Metric-Based Algorithm (Phase I):

In Phase I of the competition, our top scores for the 10 cases came from different algorithms (Table 1). While multiple image- and histogram-based metrics could distinguish mediocre results from better/best results, we did not find a metric that could reliably select the highest scoring result. More than metrics were evaluated by average case score and Spearman correlation (Tables 2 and 3). No metric performed satisfactorily when picking among the highest possible scores. Therefore we abandoned the metric-based strategy and focused on creating the single most robust algorithm.

Phase II Algorithm:

A few weeks prior to the first Phase II deadline (March 15, 2013), it was discovered that essentially all top scores for the Phase I cases could be matched using a single algorithm by Berglund et al. [11] that uses a quadratic psuedo-boolean optimization (QPBO) method (Berglund_QPBO) if the estimated fieldmap and R2* map from the Berglund_QPBO algorithm are passed through a final least squares decomposition step to estimate the fat and water components in the exact way used by the Hernando code in the Fat-water toolbox. There were three opportunities to submit an algorithm in Phase II.

Phase II Deadline 1 – March 15, 2013:

Berglund_QPBO was applied slice-wise (2D) with all available evenly-spaced echo times as long as the number of evenly spaced echoes was >=3 (guaranteed by the challenge organizers).

Phase II Deadline 2 – March 29, 2013:

Because the Berglund_QPBO algorithm did make at least one observable fat-water swap on Case 03 while the Hernando_GC algorithm did not (Figure 1), a combination algorithm was created in which both the Berglund_QPBO and Hernando_GC algorithms were performed in 2D followed by a voxel-by-voxel selection of the result with the lowest residual. To overcome isolated swap errors with lower residual, a 3x3 "voting kernel" was used to select the algorithm result for the central voxel based on the majority in the local neighborhood. To address a low score on 1.5T liver images (Case 12) that we hypothesized is likely an iron-overloaded liver, an initial maximum R2* calibration step was added to find the R2* value that includes 99.75% of R2* values within the mask provided for each case. R2* calibration used a max R2* = 800 s^{-1} and used Berglund_QPBO as long as # of evenly spaced echoes was >=4, a condition satisfied for all cases except Case 17 (nTE=3, thus no R2* fitting was performed.

Phase II Deadline 3 – April 5, 2013:

For the final submission, we returned to using just Berglund_QPBO while keeping the R2* calibration previously added to account for Case 12.

RESULTS

	PHASE I CASE NUMBER										
Algorithm	1	2	3	4	5	6	7	8	9	10	AVERAGE
Berglund_QPBO_COMPLEXFIT [11]	9502	9645	7565	9670	9678	9960	9957	9998	10000	9604	9557.9
Hernando_GRAPH_CUT_R2_000_200 [9]	9984	8725	9648	9995	8999	9989	9512	8293	9678	9973	9479.6
Hernando_GRAPH_CUT_R2_000_200_QPBOFM [9,11]	9985	9023	9700	9998	9780	9988	9867	5913	9772	9973	9399.9
slicewise_Berglund_QPBO [11]	9632	9945	8409	9803	6450	9953	9608	9866	9927	9845	9343.8
Hernando_GRAPH_CUT_R2_000_300_QPBOFM [9,11]	9985	9786	7509	9995	9991	9988	9954	9704	2425	9960	8929.7
Berglund_QPBO [11]	9632	9944	8422	9803	6450	9953	9608	9624	3576	9845	8685.7
slicewise_Berglund_ASR [8]	9108	4425	7163	9618	4548	9950	8693	9927	9935	9268	8263.5
Berglund_ASR [8]	9110	4425	7275	9618	4349	9951	8754	9924	3588	9268	7626.2
TsaoJiang [7]	9679	8240	6421	9751	6293	9793	4343	5103	3458	9214	7229.5
Sharma [6]	9592	5183	8541	9770	5067	9943	4343	5103	3458	8410	6941.0
Doneva [3]	9179	4426	4826	9689	3317	9949	7150	6590	1838	9402	6636.6
Hu [4-5]	9621	6293	7044	9789	3140	9944	4090	2896	3474	9316	6560.7
Doneva_wavelet [3]	9201	3213	4727	9687	3371	9935	7183	5847	1606	9407	6417.7
Lu [2]	9310	4466	6673	8812	3756	9893	4416	3038	5138	8267	6376.9
BEST SCORE	9985	9945	9700	9998	9991	9989	9957	9998	10000	9973	9953.6

Table 1. Scores for Phase I test cases for the tested algorithms leading up to Phase II of the challenge. Some of the tested algorithms in Phase I were a hybrid of the Hernando [9] and Berglund algorithms [11].

Table 1 reports the scores for the algorithms tested in Phase I. It should be noted that each algorithm includes many settings to customize, and we may have not been applying all algorithms optimally. However, it was clear to us that we could get the highest scores using Berglund_QPBO, Hernando_GC, or a combination of the two. Tables 2 and 3 report results for the most promising metrics applied to choose between the results presented in Table 1. Table 2 reports the score of the results selected by the metric, and Table 3 reports the Spearman correlation coefficient for the metric's value against all the available scores. Unfortunately, the metric-based strategy could not match the performance of hand-selecting the best scores for Phase I. Thus, the strategy was changed for Phase II as described in the METHODS section. Fatty Riot's Phase II results are reported in Table 4. Figure 1 shows an example of Case 03 where a fat-water swap error is still present in our first Phase II entry.

	PHASE I CASE NUMBER										
Metric	1	2	3	4	5	6	7	8	9	10	AVERAGE
MAX image_F_grad_3D_JPEG2000_nentropy	9985	9786	9700	9995	9991	9988	9954	9704	9772	9960	9883.5
MAX image_F_grad_3D_JPEG2000_L1	9502	9786	8409	9995	9991	9960	9954	9704	9678	9960	9693.9
MAX image_F_JPEG2000_L1	9985	9786	8541	9995	9991	9988	9954	9704	9678	9214	9683.6
MIN image_W_moment3	9985	9786	8541	9998	8999	9988	9512	9924	9935	9973	9664.1
MIN image_W_skewness	9985	9786	8541	9998	8999	9944	9512	9924	9935	9973	9659.7
MIN image_W_kurtosis	9985	9786	8541	9998	8999	9944	9512	9924	9927	9973	9658.9
MAX image_W_grad_3D_JPEG2000_nentropy	9985	9786	7509	9995	9991	9988	9954	9704	9678	9960	9655.0
MAX image_W_grad_3D_JPEG2000_L1	9985	9786	7509	9995	9991	9988	9954	9704	9678	9960	9655.0
MAX image_W_mean	9985	9786	7509	9995	9678	9953	9608	9866	9927	9960	9626.7
MIN image_F_PSD_variance	9985	9786	8409	9995	8999	9988	9954	9704	9927	9268	9601.5
MAX image_W_JPEG2000_variance	9985	9786	9700	9995	8999	9960	9512	8293	9678	9960	9586.8

Table 2. Scores for Phase I test cases as chosen by a selection of the top performing metrics. The mean score for the best metric of 9883.5 is much lower than the optimal score of 9953.6 (Table 1).

	PHASE I CASE NUMBER										
Metric	1	2	3	4	5	6	7	8	9	10	AVERAGE
MAX image_F_grad_3D_JPEG2000_nentropy	0.515	0.840	0.723	0.536	0.707	0.614	0.634	0.468	-0.289	0.476	0.522
MAX image_F_grad_3D_JPEG2000_L1	-0.399	0.703	0.750	0.534	0.757	0.788	0.634	0.688	-0.077	0.551	0.493
MAX image_F_JPEG2000_L1	0.456	0.857	0.433	0.523	0.883	0.711	0.871	0.658	0.259	0.256	0.590
MIN image_W_moment3	-0.234	-0.829	0.560	-0.417	-0.828	-0.397	-0.711	-0.856	-0.878	-0.754	-0.534
MIN image_W_skewness	-0.234	-0.863	0.560	-0.417	-0.863	-0.271	-0.742	-0.863	-0.849	-0.754	-0.529
MIN image_W_kurtosis	-0.234	-0.863	0.464	-0.388	-0.863	-0.185	-0.742	-0.911	-0.891	-0.754	-0.537
MAX image_W_grad_3D_JPEG2000_nentropy	0.496	0.603	0.380	0.507	0.614	0.683	0.375	0.622	0.305	0.520	0.511
MAX image_W_grad_3D_JPEG2000_L1	0.403	0.680	-0.068	0.430	0.674	0.736	0.658	0.702	0.437	0.745	0.540
MAX image_W_mean	0.260	-0.063	0.231	0.359	0.702	0.689	0.871	0.757	0.603	0.296	0.470
MIN image_F_PSD_variance	-0.458	-0.846	-0.442	-0.589	-0.652	-0.463	-0.397	-0.327	-0.124	-0.015	-0.431
MAX image_W_JPEG2000_variance	0.198	0.752	0.710	0.523	0.856	-0.557	0.669	0.140	0.644	0.701	0.464

Table 3. Spearman correlation coefficients between metric values and Phase I scores for the top performing metrics. Though correlation is high for some invidividual cases, the mean correlation is weak.

RESULTS cont.

	PHASE I CASE NUMBER										PHASE II CASE NUMBER							
Fatty Riot Phase II Submission	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	AVERAGE
March 15, 2013	9983	9978	9665	9993	10000	9984	9992	9998	10000	9972	9985	9014	9999	9991	9985	9956	9853	9902.8
March 29, 2013	9983	9982	9555	9991	10000	9989	9992	9998	10000	9971	9941	9652	9998	9989	9985	9957	9840	9930.8
April 5, 2013	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
BEST SCORE	9983	9982	9665	9993	10000	9989	9992	9998	10000	9972	9985	9652	9999	9991	9985	9957	9853	9940.9

Table 4. Team Fatty Riot's Phase II. In Phase II, all 10 cases from Phase I were tested along with 7 additional Phase II cases (11-17). Fatty Riot was in 2nd place after the March 15th submission and 1st place after the March 29th submission. The final April 5th scores and challenge winner will be announced on Thursday, April 25th at ISMRM.

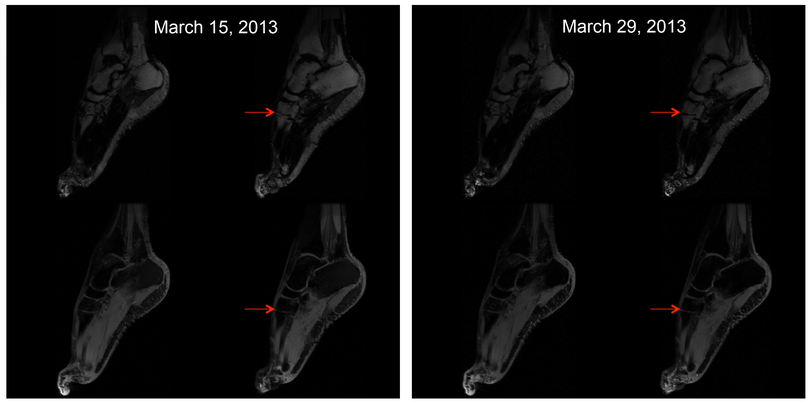

Figure 1. Fat (top) and water (bottom) images for Case 03 resulting from the Fatty Riot March 15, 2013 (left) and March 29, 2013 (right) submissions in Phase II of the challenge. March 15th scores higher (9665) than March 26th (9555) even though the March 15th result has a swap error (red arrows).

DISCUSSION

The summary presented here of the Fatty Riot team participation in the ISMRM Fat-Water Challenge omits sidetracks we pursued and the details of many features added to improve the robustness and speed of our algorithm to handle as many scenarios of input we could imagine. One noteworhty parameter for the Berglund_QPBO algorithm is the spatial regularization parameter (μ) which controls fieldmap smoothness. We tested a range of μ values and set μ=10 in our Phase II entries. The Berglund_QPBO version we employed also included a multi-resolution pyramid strategy in which the input data is recursively down-sampled until reaching a single point. Then the result is fed into the next higher level of the resolution pyramid. We plan to contribute the Berglund_QPBO algorithm to the next version of the ISMRM Fat-Water toolbox.

No matter the outcome of the challenge in regards to the announced winning team, participation in the challenge directly improved the fat-water separation algorithm we apply in our research. We want to thank all the contest organizers for their hard work establishing and executing the challenge. Many of the world's experts on fat-water MRI were organizers of the challenge and therefore not eligible to participate as competitors – thus opening the door for other groups to have a better chance at winning! We especially want to thank Samuel A. Hurley (Univ. of Wisconsin) for his hard work and patience running all the Phase II tests.

REFERENCES

[1] Samsonov A and Tsao. ISMRM Challenge 2012.http://www.ismrm.org/challenge
[2] Lu W, et al. MRM 60(1):236-44; 2008. [3] Doneva M, et al. MRI 64(6):1749-59; 2010. [4] Yu, et al. MRM 54(4):1032-1039; 2005. [5] Reeder SB, et al. MRM 51(1): 35-45; 2004. [6] Sharma SD, et al. MRM 67(3):650-9; 2012. [7] Tsao J and Jiang Y. MRM Aug 6 2012 [Epub ahead of print] [8] Berglund J, et al. MRM 63(6):1659-68; 2010. [9] Hernando D, et al. MRM 63(1):79-90; 2010. [10] Hernando D, et al. ISMRM Fat Water Toolbox v1.0. http://ismrm.org/workshops/FatWater12/data.htm 2012.
[11] Berglund J, et al. MRM 67(6):1684-93; 2012.

Vanderbilt University Institute of Imaging Science
VUIIS Building, Medical Center North
1161 21st Ave, South
Nashville, TN 37232-2310
Tel: (615) 322-8359
Fax: (615) 322-0734
URL: www.vuiis.vanderbilt.edu