Vendor-Neutral Implementation of SNR-Efficient Fat Quantification in Pulseq

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  - Zhao R, Zhang Y, Wang X, et al. Motion-robust, high-SNR liver fat quantification using a 2D sequential acquisition with a variable flip angle approach. *Magn Reson Med.* 2020;84(4):2004-2017. doi:10.1002/mrm.28263

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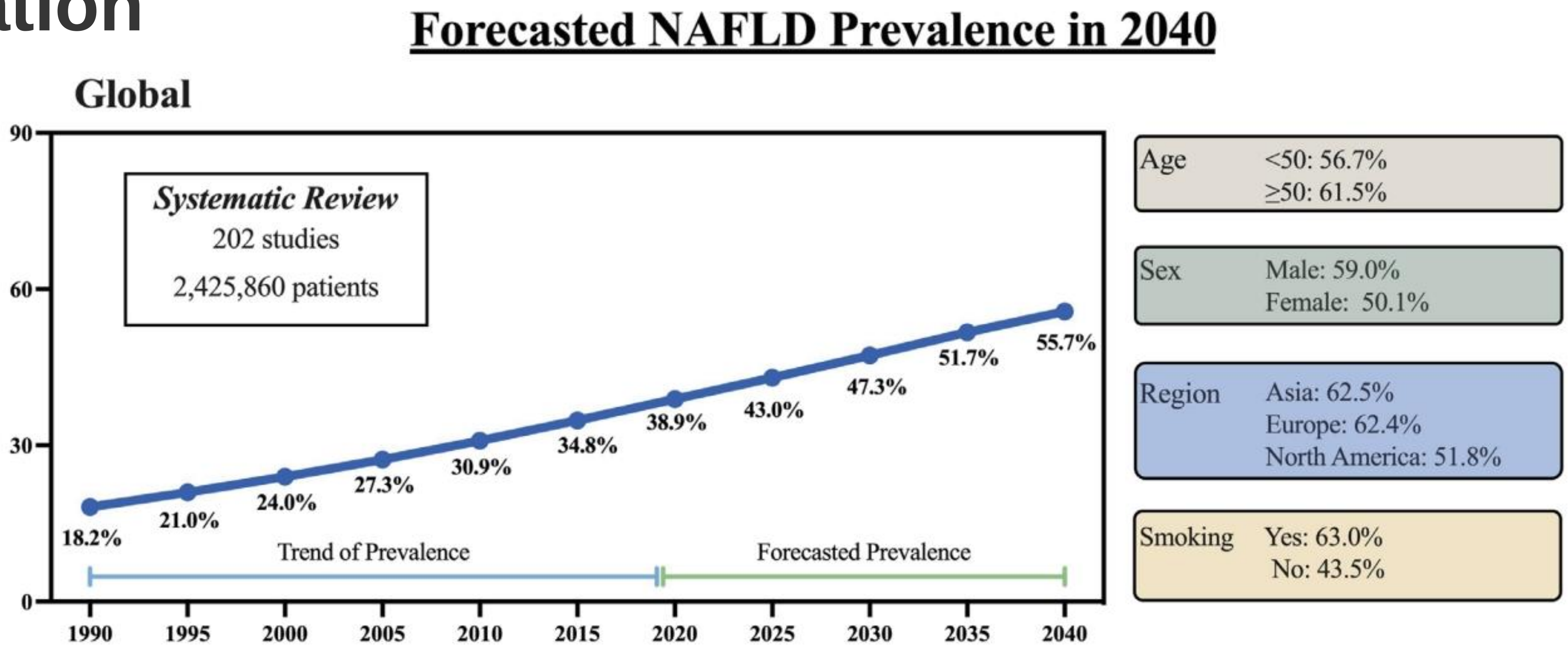
Motivation

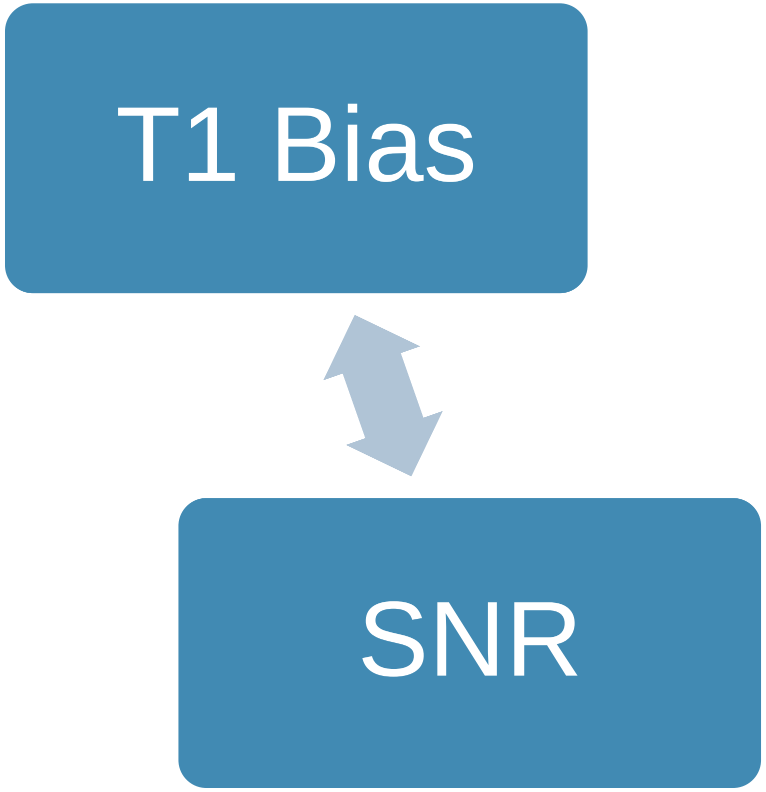


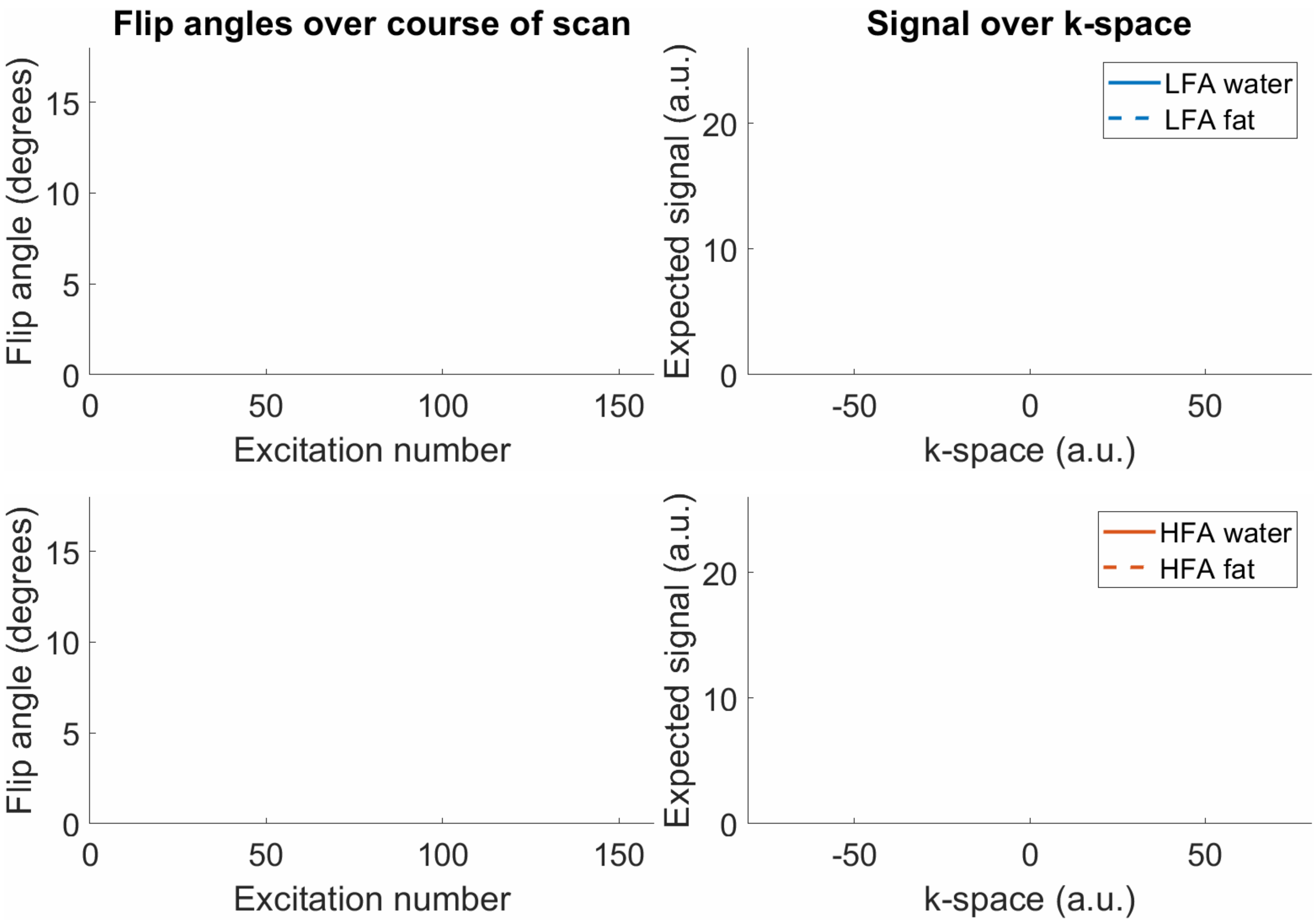
Motion-robust, accurate, **cross-vendor reproducible** MR-based fat quantification urgently needed

Le MH, Yeo YH, Zou B, et al. Forecasted 2040 global prevalence of nonalcoholic fatty liver disease using hierarchical bayesian approach. *Clin Mol Hepatol.* 2022;28(4):841-850. doi:10.3350/cmh.2022.0239

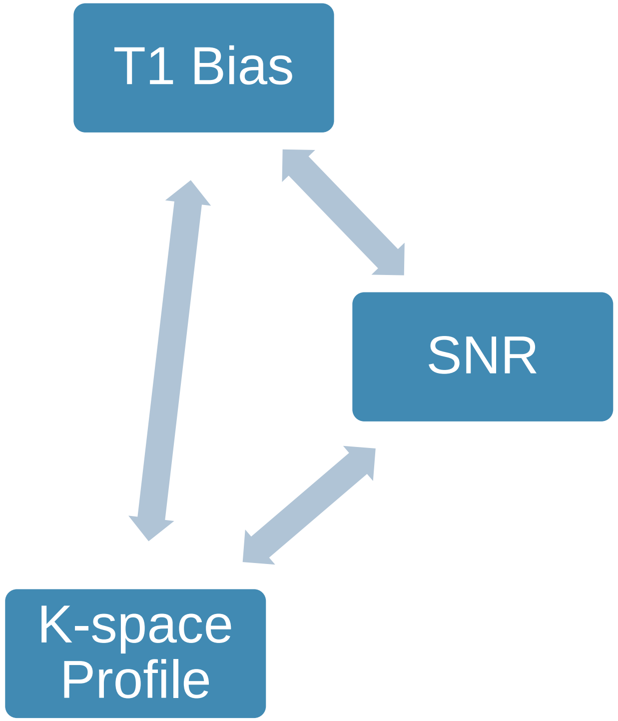
Constant FA, Linear Encoding (Steady State)

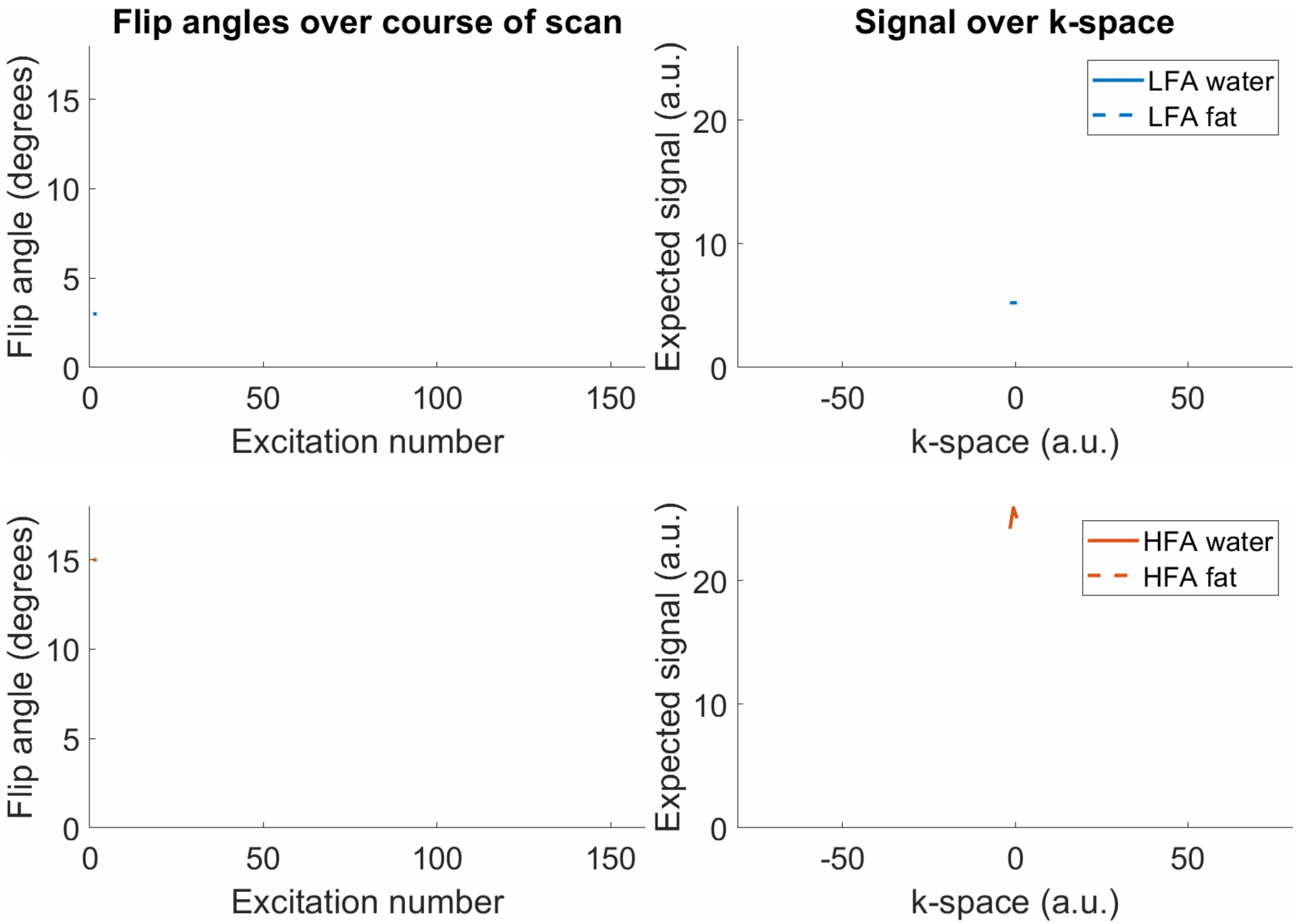
2D sequential 6-echo spoiled gradient echo sequence



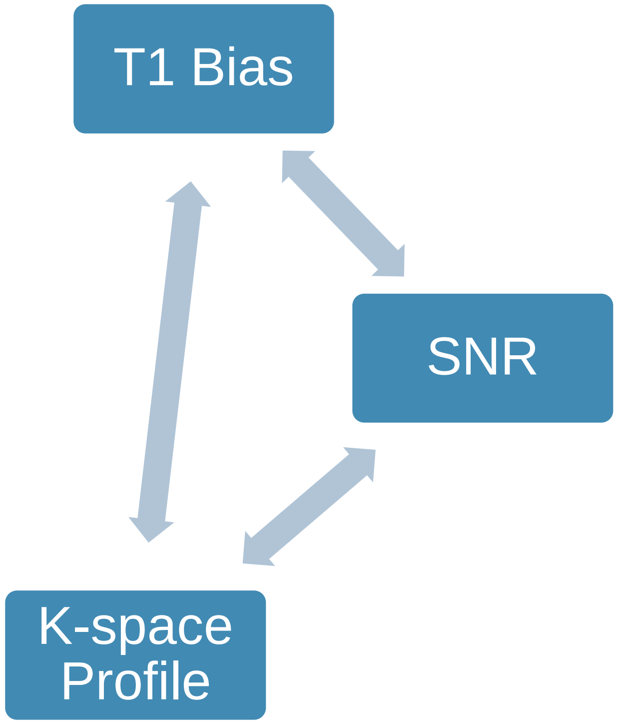


Constant FA, **Centric Encoding** (Non-Steady State)

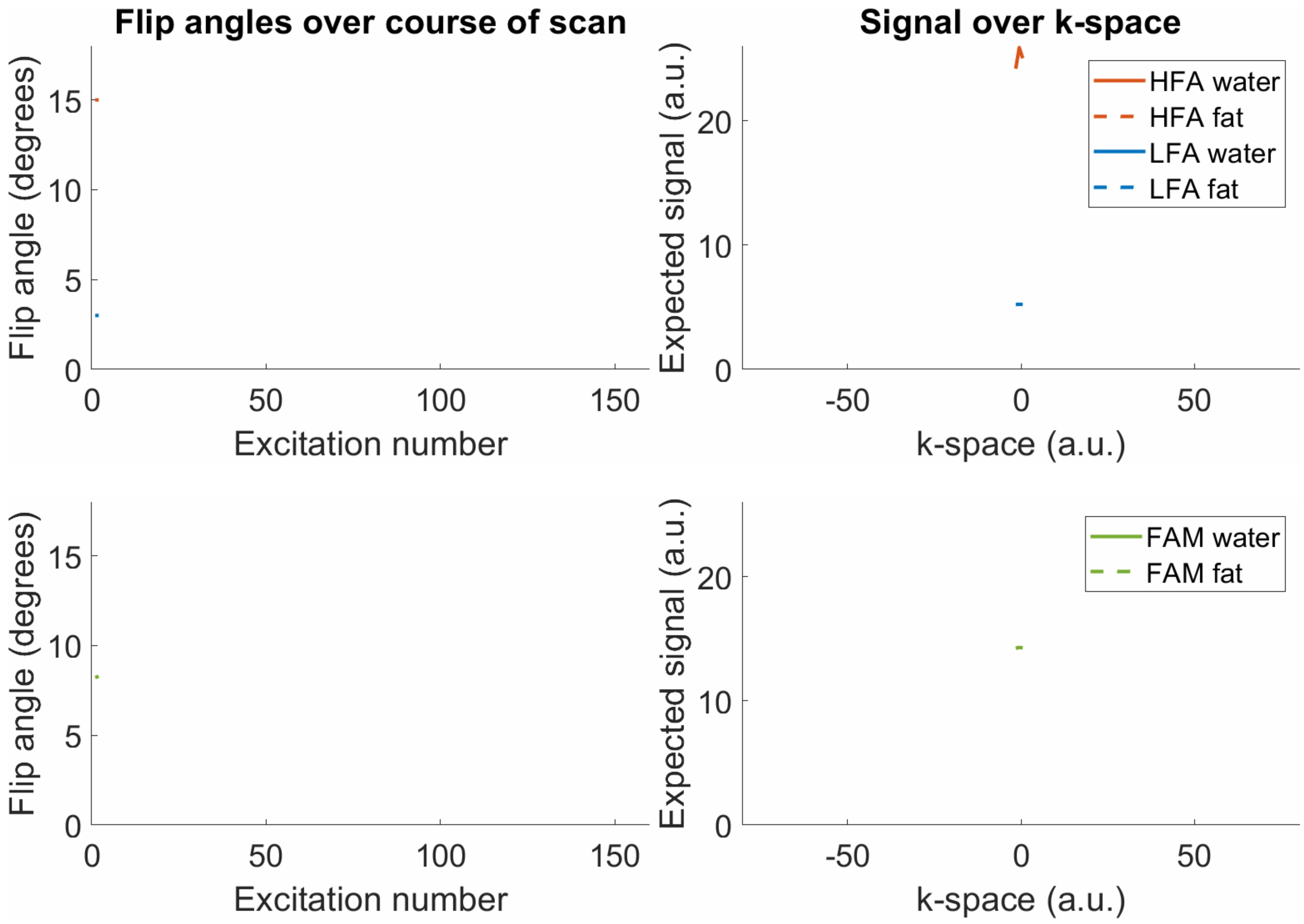




Flip Angle Modulation, Centric Encoding (Non-Steady State)



Flip angle modulation is determined by cost function balancing these factors



```
if FA_SCHEME == "v"
    fam_alphas = [ 9.17745046  9.26863982  9.36001542  9.45565493  9.54323117  9.63717383 ...
    9.71881626  9.81095649  9.88708398  9.97803693 10.04897537 10.13895461 ...
    10.20463764 10.29354696 10.35368694 10.44131505 10.49561803 10.58178627 ...
    10.63000632 10.71458573 10.75654003 10.83944674 10.87499766 10.95616004 ...
    10.98517414 11.06450891 11.08685388 11.16426104 11.179797   11.25515225 ...
    11.26372629 11.3368954  11.33836008 11.40919305 11.4034025  11.47175452 ...
    11.45857155 11.52429318 11.5036031  11.56654912 11.53825032 11.59828036 ...
    11.56228751 11.6192647  11.57551346 11.62930094 11.57774259 11.62821752 ...
    11.56882282 11.61586343 11.54863153 11.59212317 11.51706819 11.55691375 ...
    11.47408212 11.51019576 11.41966515 11.45197632 11.35385439 11.38231916 ...
    11.27674969 11.30134313 11.18850774 11.20923648 11.08935538 11.10625052 ...
    10.97958058 10.9927064  10.85954423 10.86899179 10.72966915 10.73556036 ...
    10.59044077 10.59292221 10.44240274 10.44164722 10.28614811 10.28235005 ...
    10.12231138 10.115683    9.95156309  9.94232983  9.77459298  9.76299006 ...
    9.59210564  9.57837584  9.40481165  9.38919749  9.21331334  9.19606455 ...
    9.0183434   8.99968503  8.82062638  8.80078979  8.62081667  8.60002103 ...
    8.41953837  8.39799767  8.21738969  8.19530071  8.01492841  7.99247797 ...
    7.8126774   7.79003545  7.61111636  7.58843817  7.41068654  7.38810925 ...
    7.21178416  7.18943146  7.01476457  6.99274054  6.81994028  6.79833525 ...
    6.62758367  6.606473    6.43793022  6.41737406  6.25117977  6.23122585 ...
    6.06749793  6.04818298  5.88702148  5.86837114  5.70986029  5.69189036 ...
    5.53610058  5.51881886  5.36580564  5.34921431  5.19902353  5.18311812 ...
    5.03578451  5.02055651  4.87610557  4.86154183  4.71999379  4.70607922 ...
    4.5674436   4.55416079  4.41844462  4.40577316  4.27297649  4.26089451];
    % optimized variable flip angles for res = 144, TR = 12 ms, field strength = 3T, no parallel imaging acceleration
elseif FA_SCHEME == "h"
    fam_alphas = repmat(15, [1 144]); % for high flip angle
elseif FA_SCHEME == "l"
    fam_alphas = repmat(3, [1 144]); % for low flip angle
else
    error("FA_SCHEME must be 'v', 'h', or 'l'")
end
```

```matlab
if ENCODING_SCHEME == "l"
    peScales = peScales - (peScales(1) + peScales(end))/2;
elseif ENCODING_SCHEME == "c"
    peScalesTemp=peScales;
    peScales(1:2:end) = peScalesTemp(length(peScalesTemp)/2+1:end);
    peScales(2:2:end) = peScalesTemp(length(peScalesTemp)/2:-1:1); % rearrange for centric encoding
    peScales = peScales + peScales(3)/2; % to make the k-space sampling along PE direction symmetric
else
    error("ENCODING_SCHEME must be 'c' or 'l'")
end
```

Implementing centric encoding is easy

(just remember to reorder data in reconstruction)

```
for i=1:Ny
    [rf, gz] = mr.makeSincPulse(fam_alphas(i)*pi/180,'Duration',rfDuration,...
        'SliceThickness',sliceThickness,'apodization',0.42,'timeBwProduct',4,'system',sys);
    % ...
    seq.addBlock(gxPre,mr.scaleGrad(gyPre,peScales(i)),gzReph);
    % ...
    seq.addBlock(mr.makeDelay(delayTR(c)),gxSpoil,mr.scaleGrad(gyPre,-peScales(i)),gzSpoil);
end
```

Adding FAM is easy too!

Rapid Prototyping and Experiments

Aug
- Single slice and multi-slice FAM developed

Sept
- Debugging/refinement at UW
- Shorten TEs and add dummy slices

Oct
- Experiments with flip angle/encoding schemes
- Multi-repetition, internal test-retest

Nov
- Send to Martinos Center for cross-center/vendor reproducibility
- Submit ISMRM abstract

Two-Center, Two-Vendor Study

Site	Center 1 UW-Madison	Center 2 Martinos Center
Scanner	GE Signa Premier	Siemens MAGNETOM Skyra
Field Strength	3.0 T	2.89 T
TE_1, initial echo time (ms)	1.73	1.53

Pulse sequence parameter	Values
TE, echo time	TE_1 = variable by vendor, ΔTE = 1.3 ms, N_{TE} = 6
TR, repetition time (ms)	12
Total bandwidth (kHz)	500
Flip angle	Varies by sequence
Voxel size (mm × mm × mm)	2.0 × 2.0 × 8.0
Dummy slices / acquired slices	2 / 6
Acquisition matrix	144 × 144
Acquisition duration	14 s
Temporal footprint per slice	1.7 s

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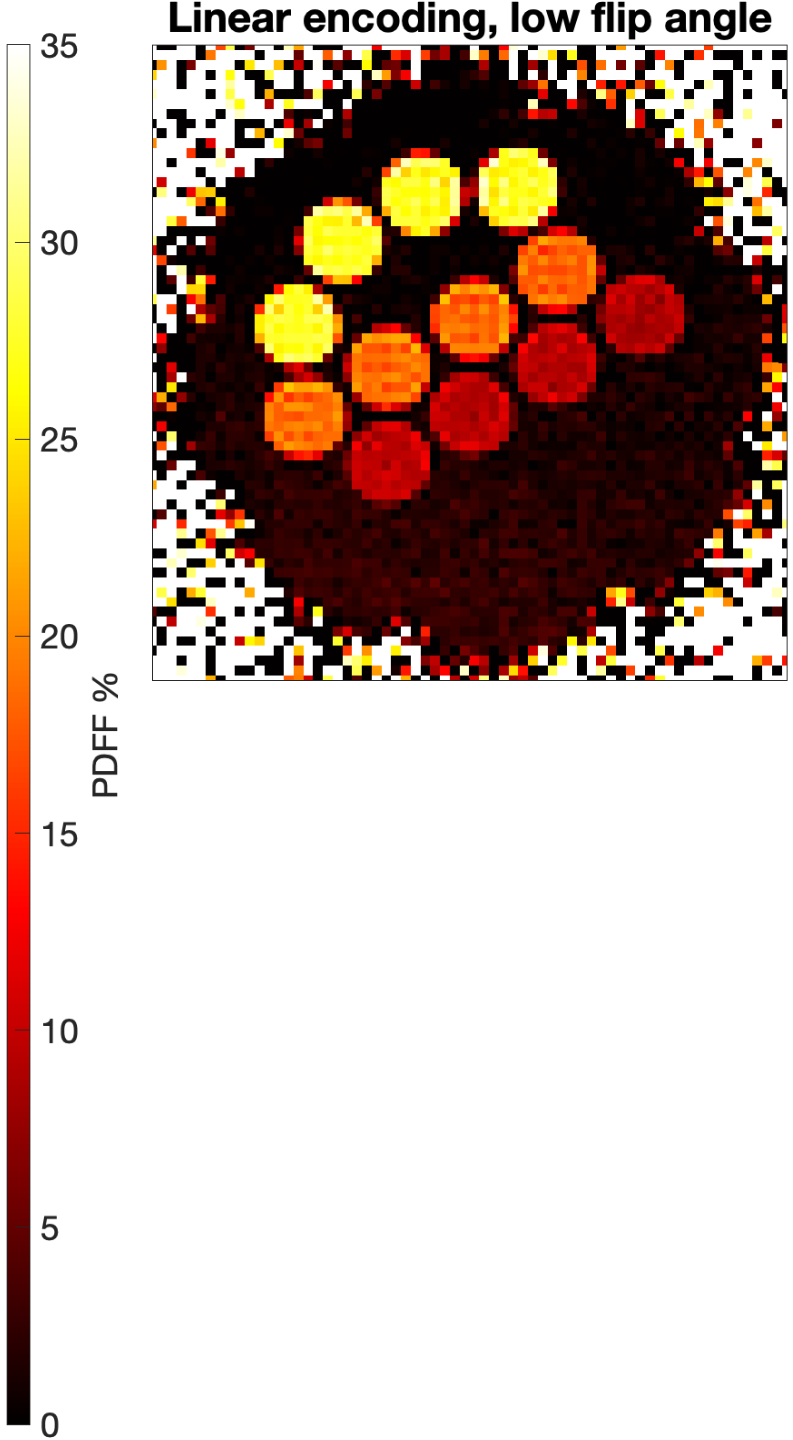
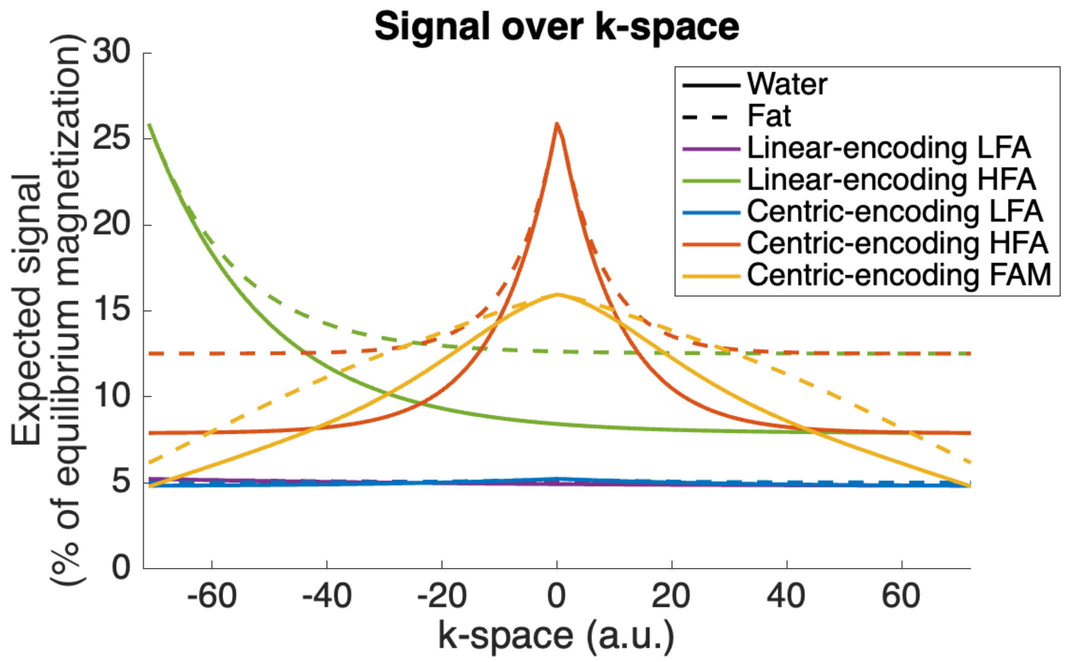
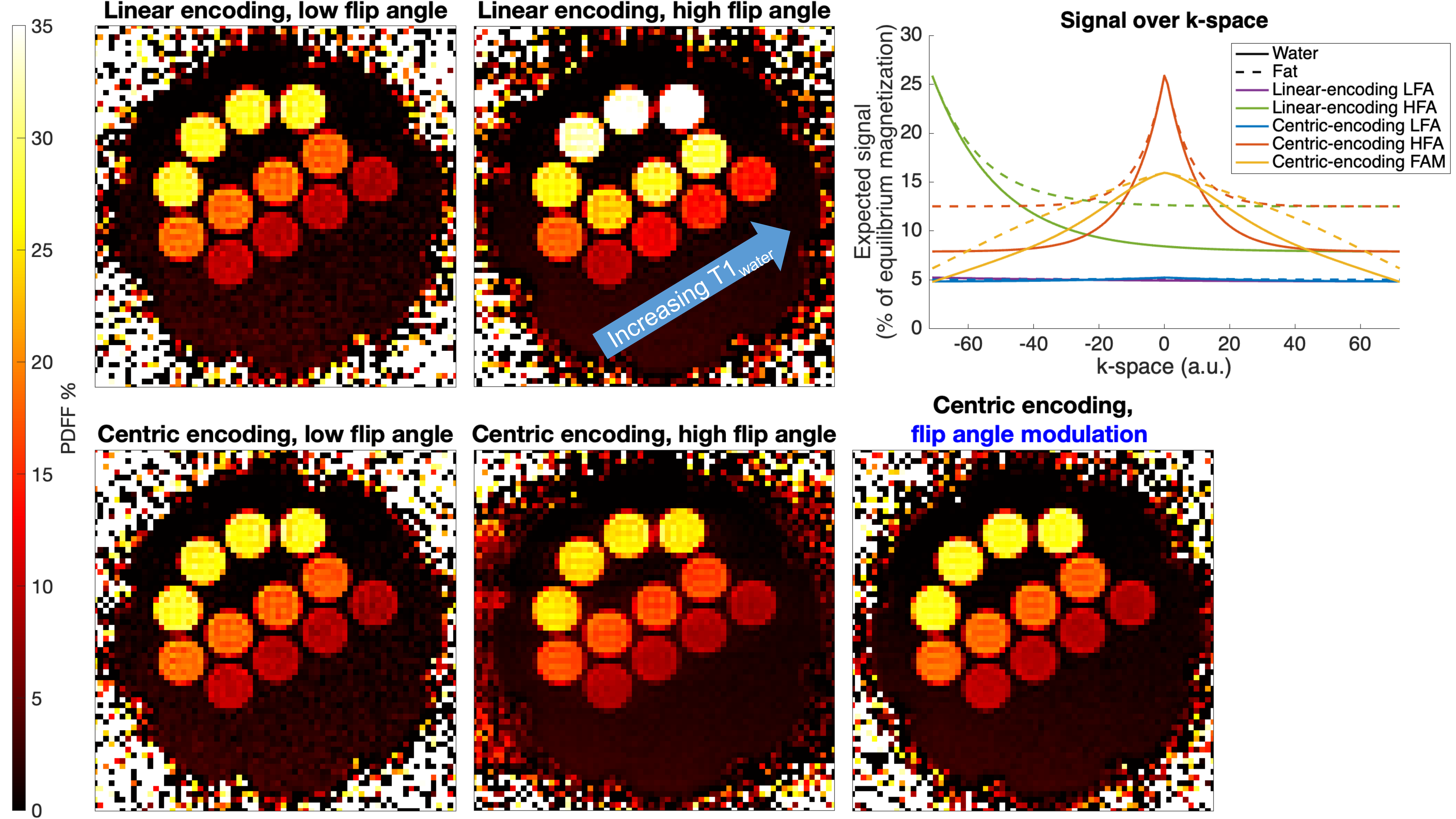
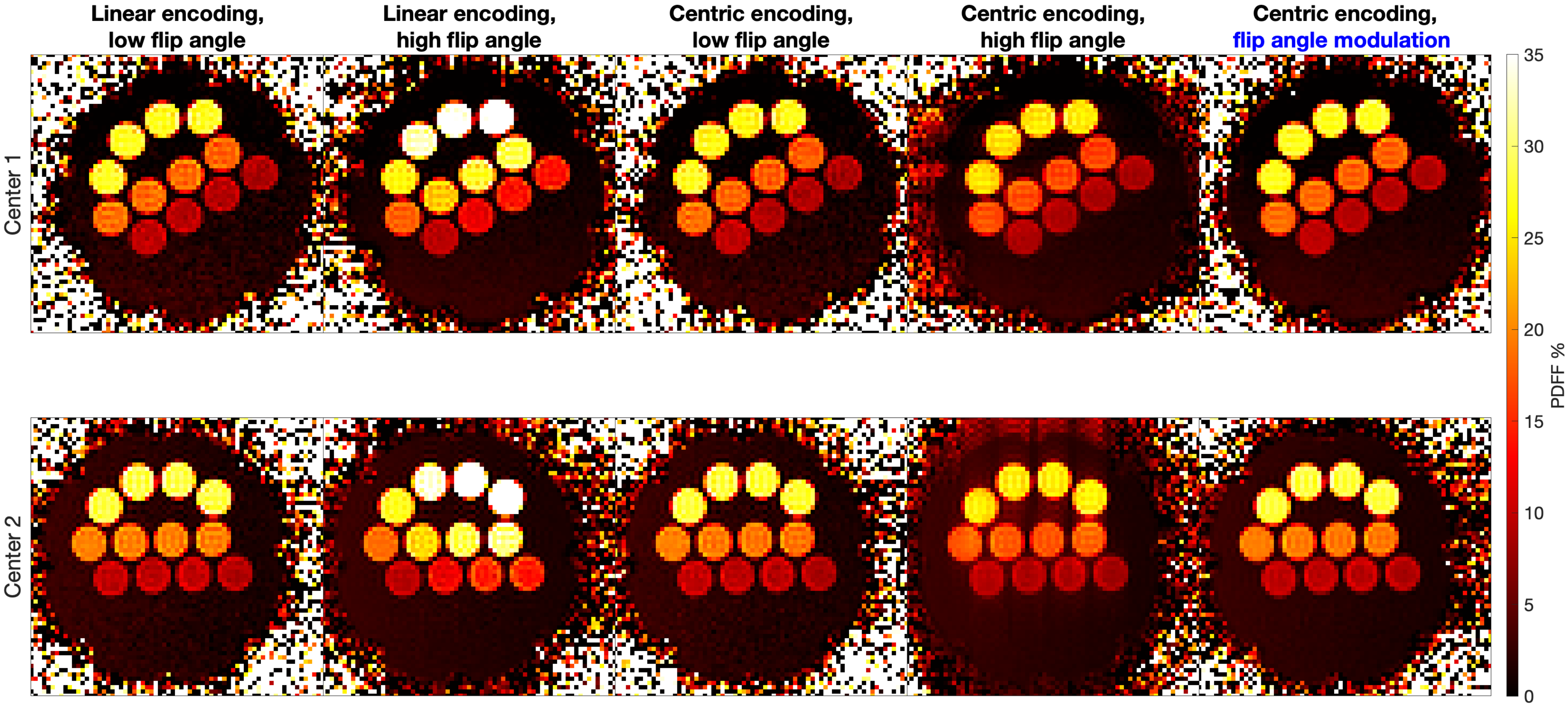
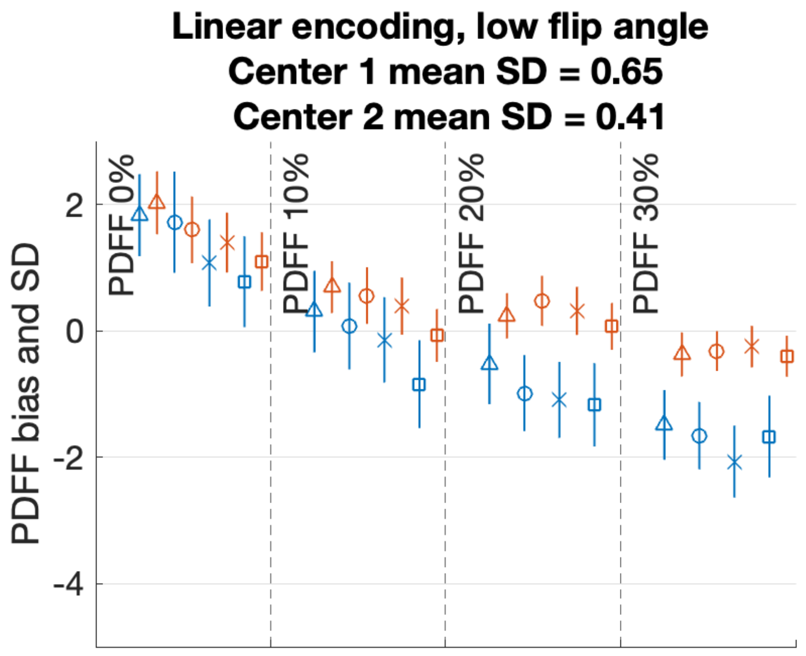

Linear encoding, low flip angle
35
30
25
20
15
10
5
0
PDFF %


Signal over k-space
Water
Fat
Linear-encoding LFA
Linear-encoding HFA
Centric-encoding LFA
Centric-encoding HFA
Centric-encoding FAM
Expected signal
(% of equilibrium magnetization)
k-space (a.u.)
30
25
20
15
10
5
0
-60
-40
-20
0
20
40
60

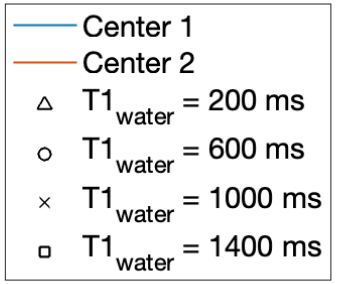

PDFF %
35
30
25
20
15
10
5
0
Linear encoding, low flip angle
Linear encoding, high flip angle
Increasing T1 water
Signal over k-space
Expected signal
(% of equilibrium magnetization)
k-space (a.u.)
Water
Fat
Linear-encoding LFA
Linear-encoding HFA
Centric-encoding LFA
Centric-encoding HFA
Centric-encoding FAM
Centric encoding, low flip angle
Centric encoding, high flip angle
Centric encoding,
flip angle modulation


Linear encoding,
low flip angle
Linear encoding,
high flip angle
Centric encoding,
low flip angle
Centric encoding,
high flip angle
Centric encoding,
flip angle modulation
Center 1
Center 2
PDFF %
35
30
25
20
15
10
5
0

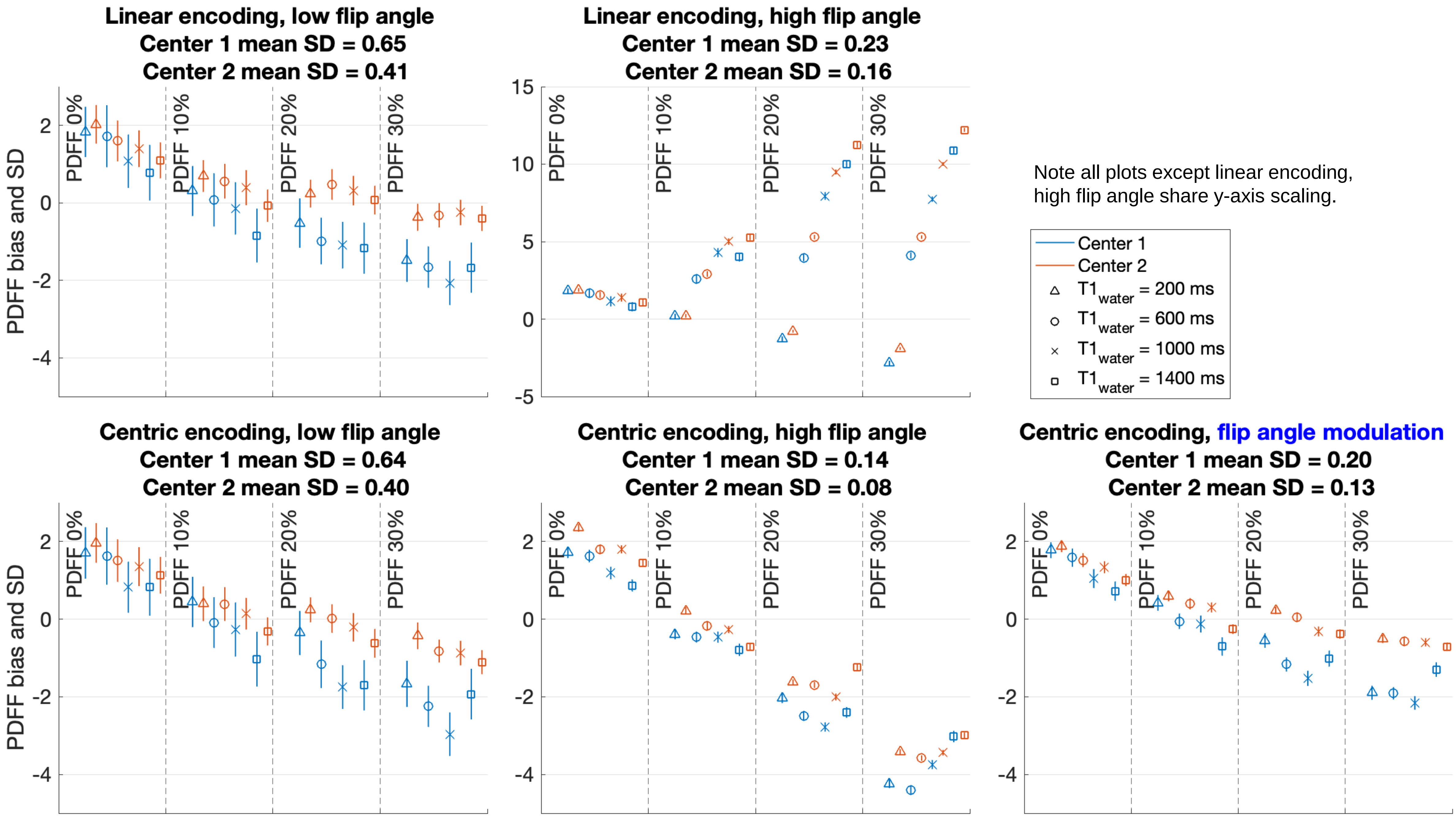
Pulseq-FAM has low bias and good SNR



Note all plots except linear encoding, high flip angle share y-axis scaling.

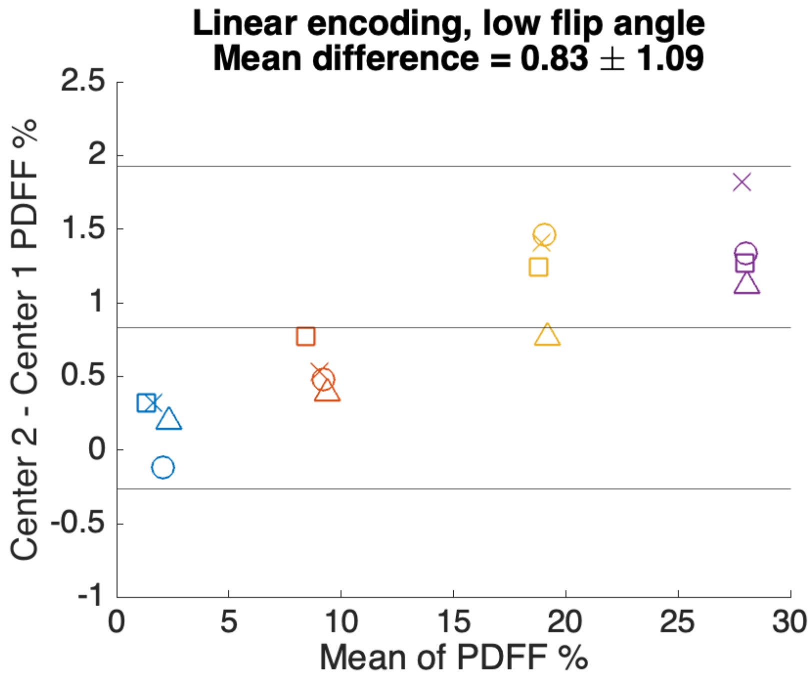


Pulseq-FAM has low bias and good SNR

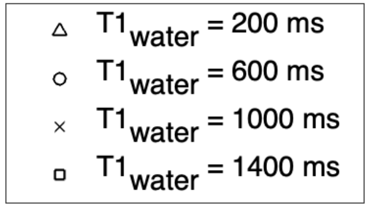


Note all plots except linear encoding, high flip angle share y-axis scaling.

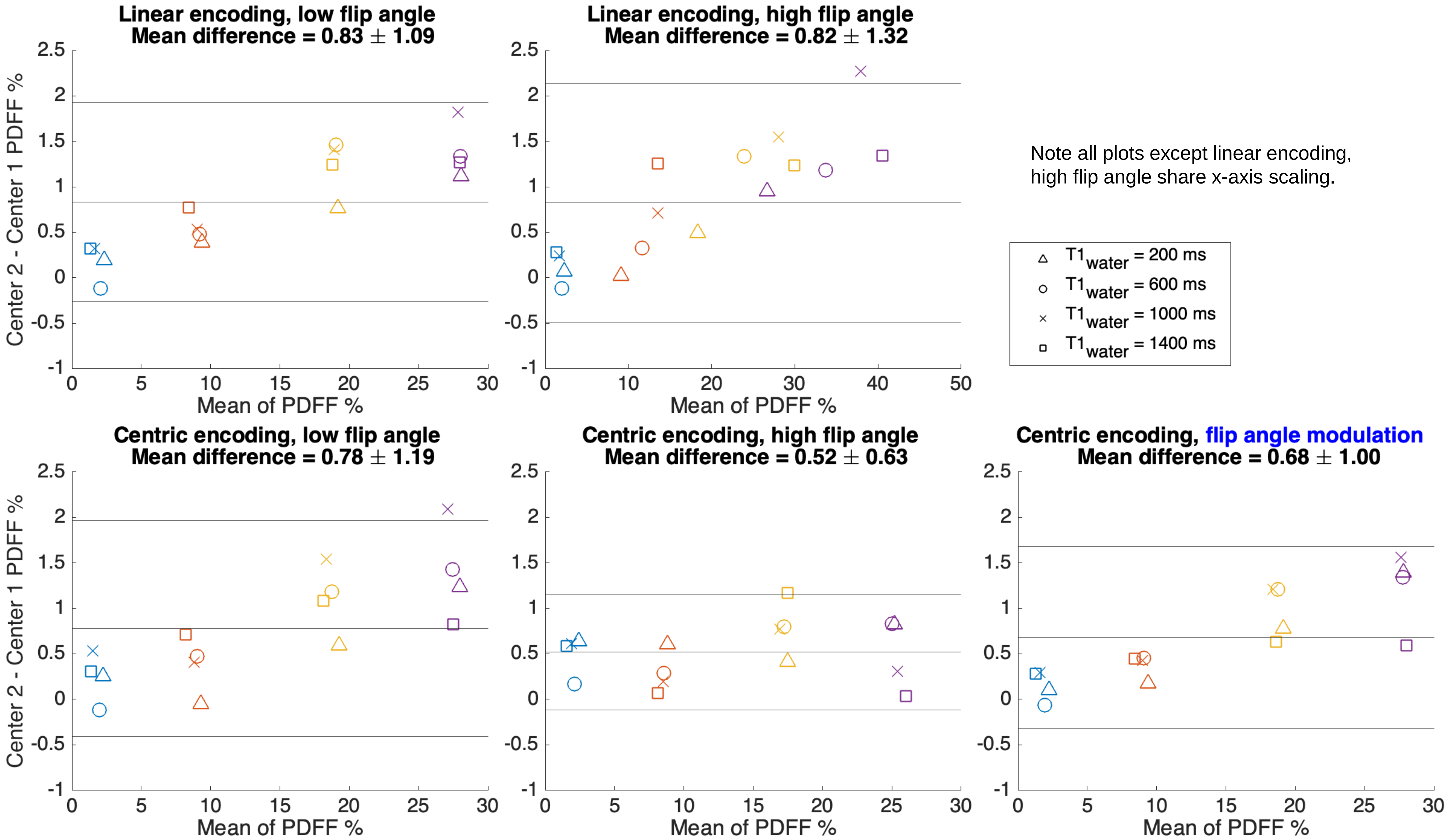
Pulseq-FAM has good repeatability



Note all plots except linear encoding, high flip angle share x-axis scaling.

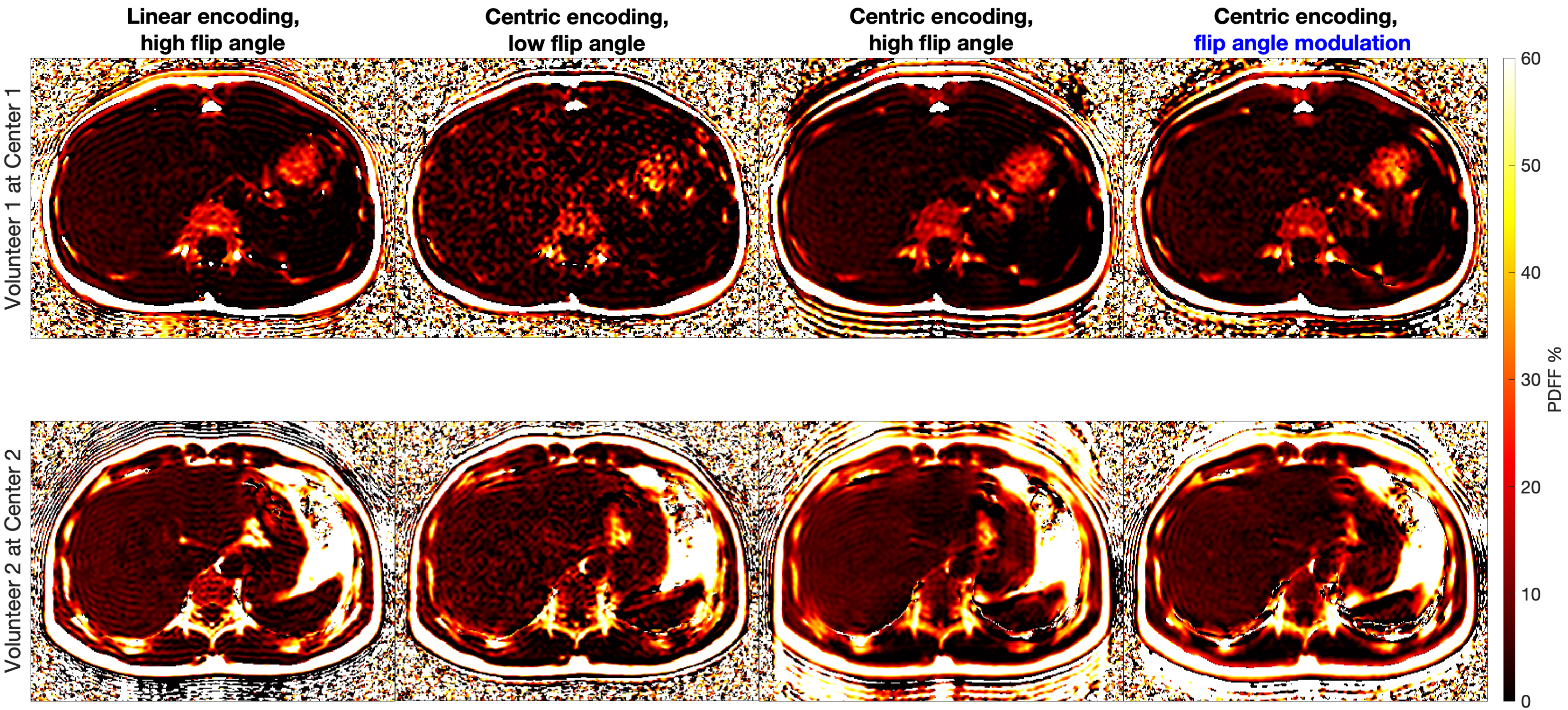


Pulseq-FAM has good repeatability

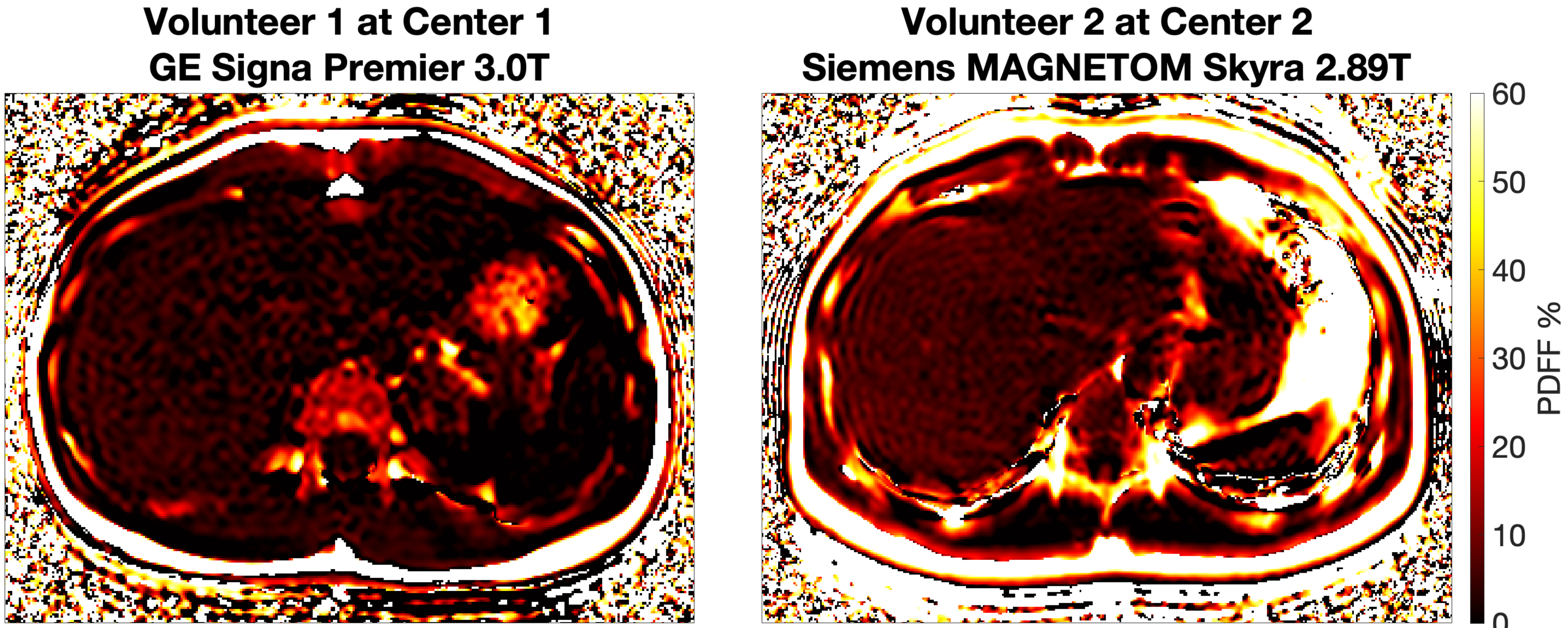


Note all plots except linear encoding, high flip angle share x-axis scaling.

Pulseq-FAM is feasible in vivo with free breathing (two different volunteers)



Free-Breathing Pulseq-FAM: Centric Encoding, Flip Angle Modulation



Discussion

- Successful, straightforward implementation of FAM in Pulseq
- SNR and accuracy of FAM matches predictions in phantoms
- Free breathing in vivo feasibility demonstrated

Future Directions

- Larger scale in vivo study
- More centers and field strengths
- Study timing mechanisms deeply to harmonize TEs
- Add scanner GUI and live recalculation of FAs
- Parallel imaging, simultaneous-multi-slice

Thank you!

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