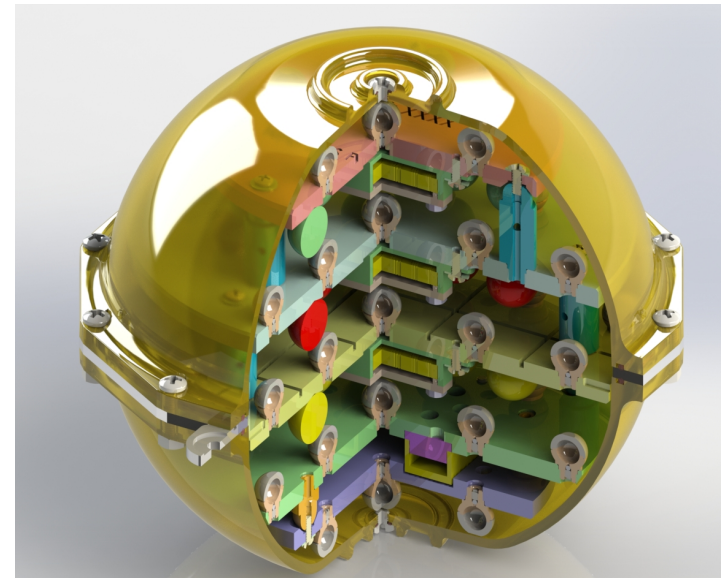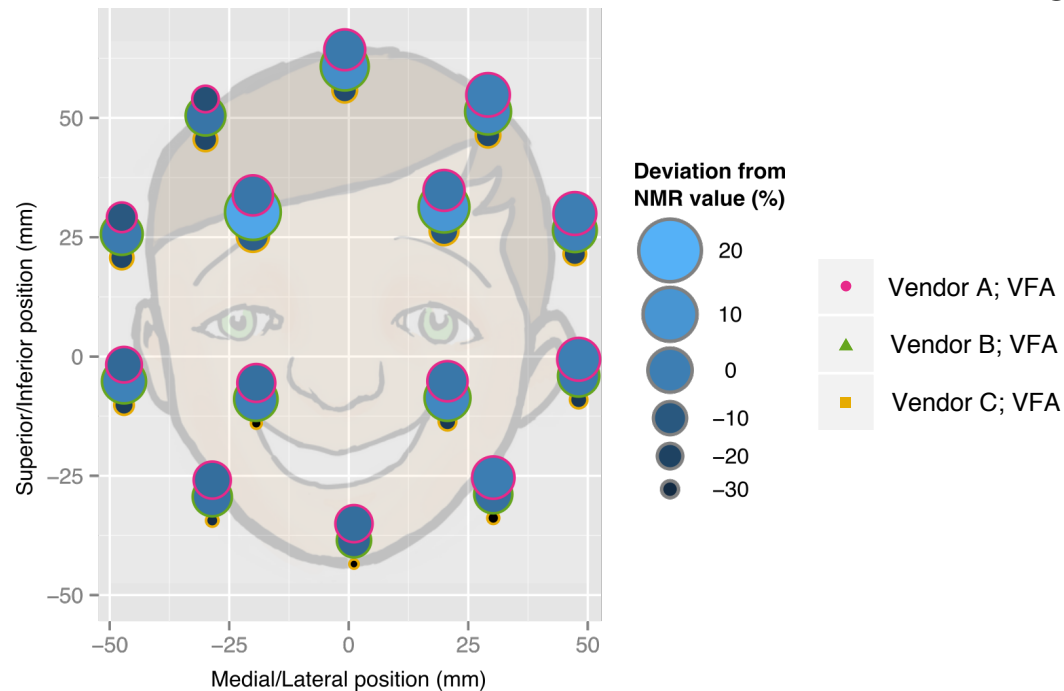# Comparison of T1 measurement using ISMRM/NIST phantom

Ad Hoc Committee on Standards for Quantitative MRI of the ISMRM

Multi-site, multi-vendor comparison of T1 measurement using ISMRM/NIST system phantom

Keenan KE[1], Stupic KF[1], Boss MA[1], Russek SE[1], Chenevert TL[2], Prasad PV[3], Reddick WE[4], Cecil KM[5], Zheng J[6], Hu P[7], Jackson EF[8], and the Ad Hoc Committee on Standards for Quantitative MRI[9]

[1]Physical Measurement Laboratory, National Institute of Standards and Technology, Boulder, CO; [2]University of Michigan, Ann Arbor, MI; [3]NorthShore University Health System, Evanston, IL; [4]St. Jude Children's Research Hospital, Memphis TN; [5]Cincinnati Children's Hospital Medical Center, Cincinnati, OH; [6]Washington University in St. Louis, St. Louis, MO; [7]University of California, Los Angeles, CA; [8]University of Wisconsin, Madison, WI; [9]International Society of Magnetic Resonance in Medicine
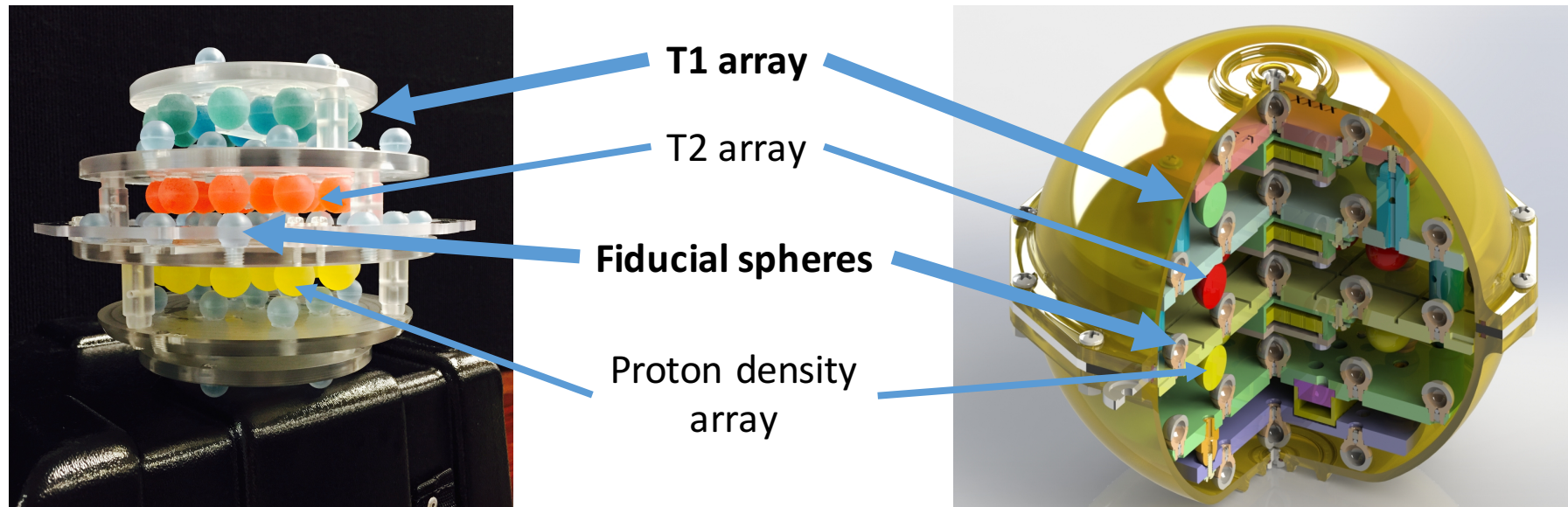
Multi-site, multi-vendor T1 measurement

- How does T1 measurement vary at one site day-to-day?

- How does T1 measurement vary across manufacturers?

- Is the variation different between 1.5 T and 3 T?

- Is the variation different between inversion recovery and variable flip angle methods?

ISMRM/NIST system phantom supports quantitative T1 and T2 measurements and can be used to answer these questions.

ISMRM/NIST System Phantom

- $NiCl_2$ solutions with varying concentrations for T1 range 20 to 2000 ms
- Reference T1 values measured on NMR by inversion recovery at 20 °C, 1.5 T and 3 T

T1 array

T2 array

Fiducial spheres

Proton density array

Photos courtesy of High Precision Devices.

Multi-site, multi-vendor Comparison

- Two system phantoms traveled the continental US

- Repeatability measurements (n=3) at one 3 T system for each manufacturer, coefficient of variation (CV)[1]

- Receive-only, head coils with 8 to 32 channels

- Reported temperature ranges: 17.1 to 23.3 °C (of MRI room or bulk water in the phantom)

	1.5 T	3 T
Vendor A	1	3
Vendor B	1	3
Vendor C	5	5

[1]Sullivan DC, Obuchowski NA, Kessler LG, et al. Metrology Standards for Quantitative Imaging Biomarkers. Radiology. 2015

T1 Measurement Protocol

Inversion Recovery	
Sequence	Fast, SE-IR, 2D
Scan Plane	Coronal
Thickness (mm)	6
TR (ms)	4500
TE (ms)	~ 7 (minimum full)
Inversion Times (ms)	35*, 50, 75, 100, 125, 150, 250, 1000, 1500, 2000, 3000
Averages	1
Echo Train Length	6
Pixel Size (mm x mm)	0.98 x 0.98

Note: TI = 35 ms not available on Vendor A.

Variable Flip Angle	
Sequence	Fast, SPGR, 3D
Scan Plane	Coronal
Thickness (mm)	3 (no gap)
TR (ms)	~ 6.6
TE (ms)	Minimum: 1.5-2.5
Flip Angles	2, 5, 10, 15, 20, 25, 30
Averages	4
Echo Train Length	1
Pixel Size (mm x mm)	0.98 x 0.98

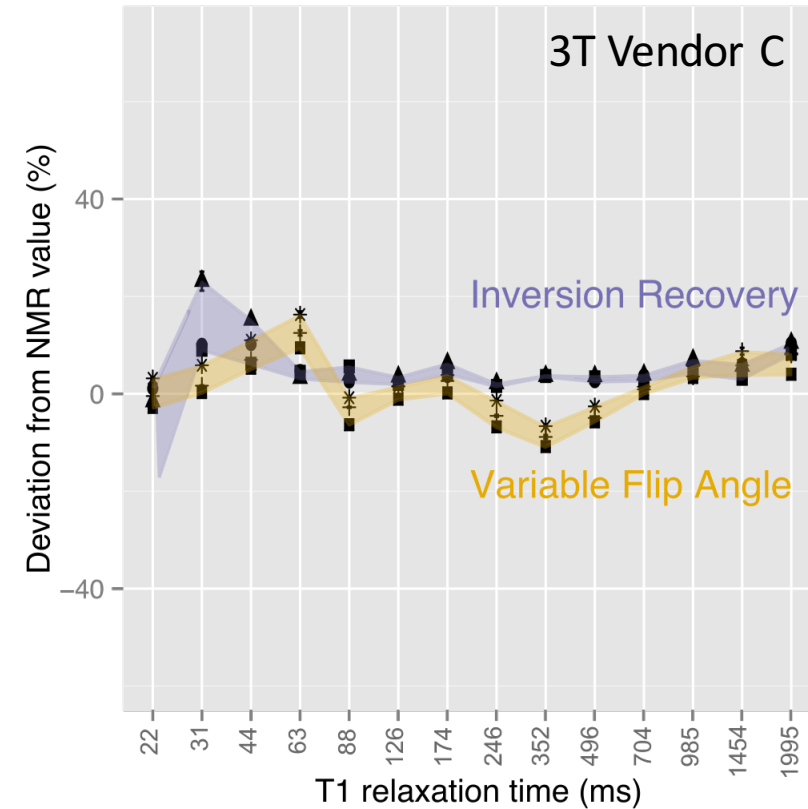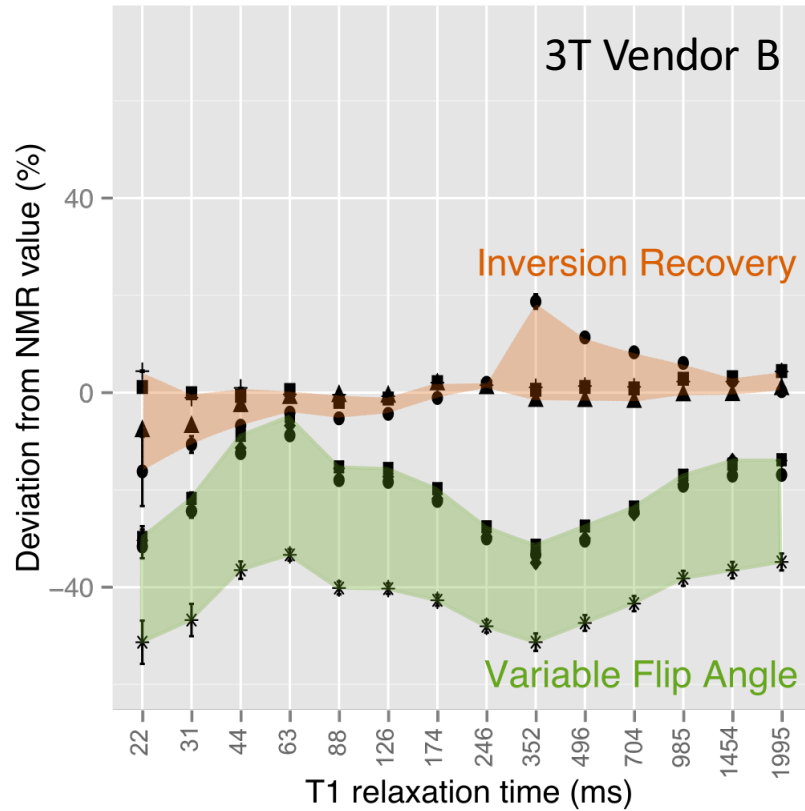Note: Prescan on FA=15°, no subsequent gain changes.

- Data fit using custom software (PhantomViewer, developed at NIST)
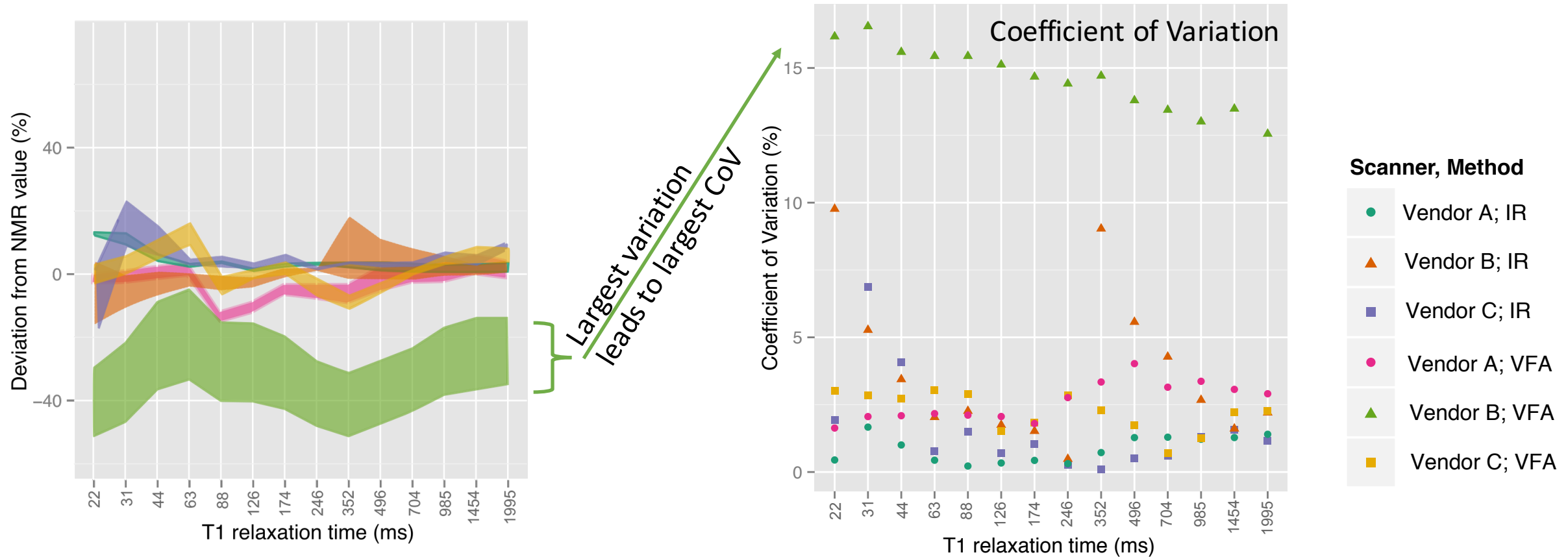
Vendor A, 3T, repeatability measurements
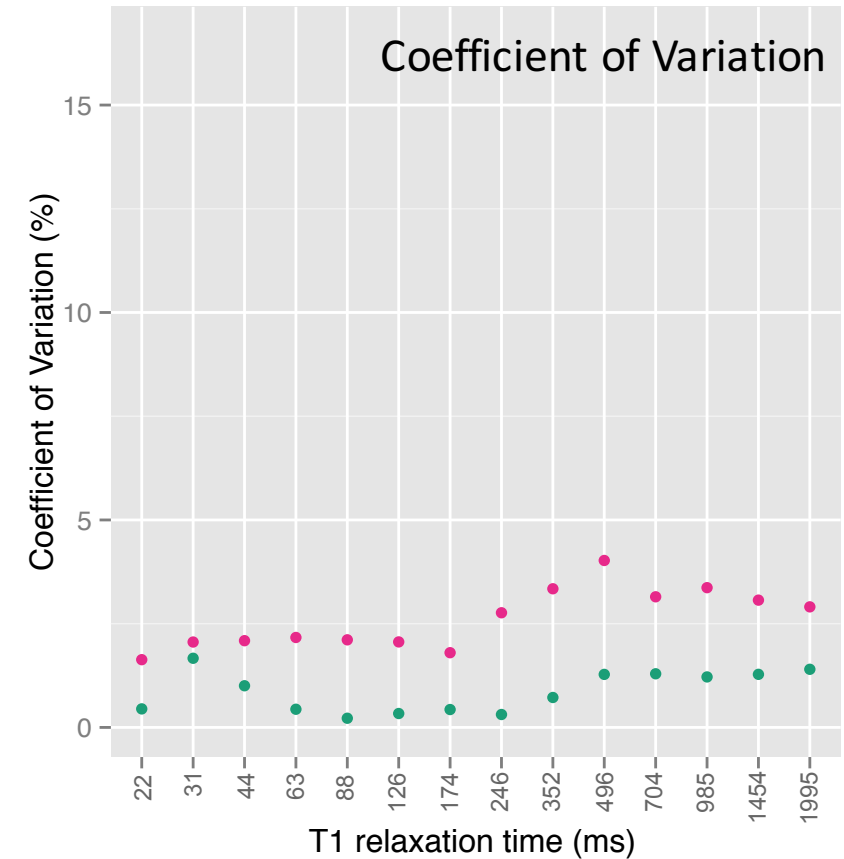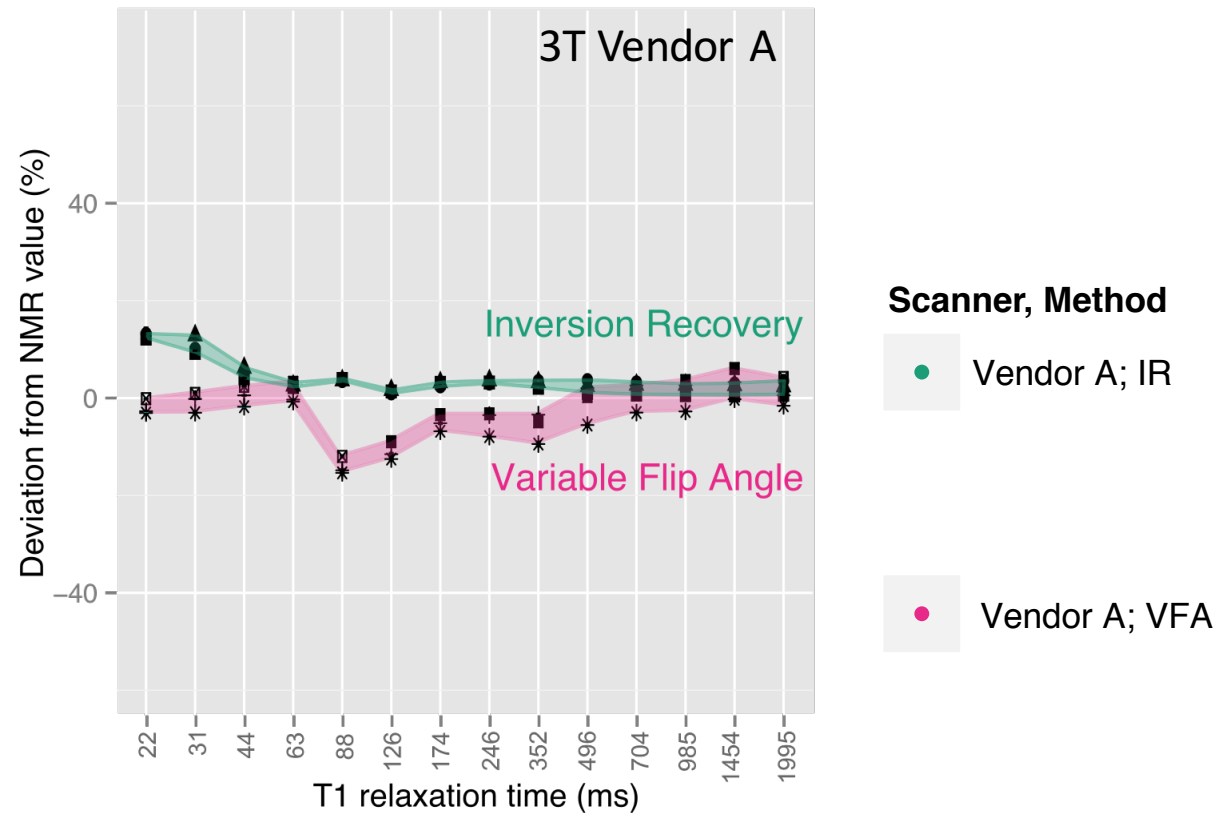
Colored bands show the range of values at a single repeatability site.

# Vendors B and C, 3T, repeatability measurements

Largest single site variation, approximately 20%!

Colored bands show the range of values at a single repeatability site.

All repeatability measurements at 3 T

Largest variation leads to largest CoV

Colored bands show the range of values at a single repeatability site.

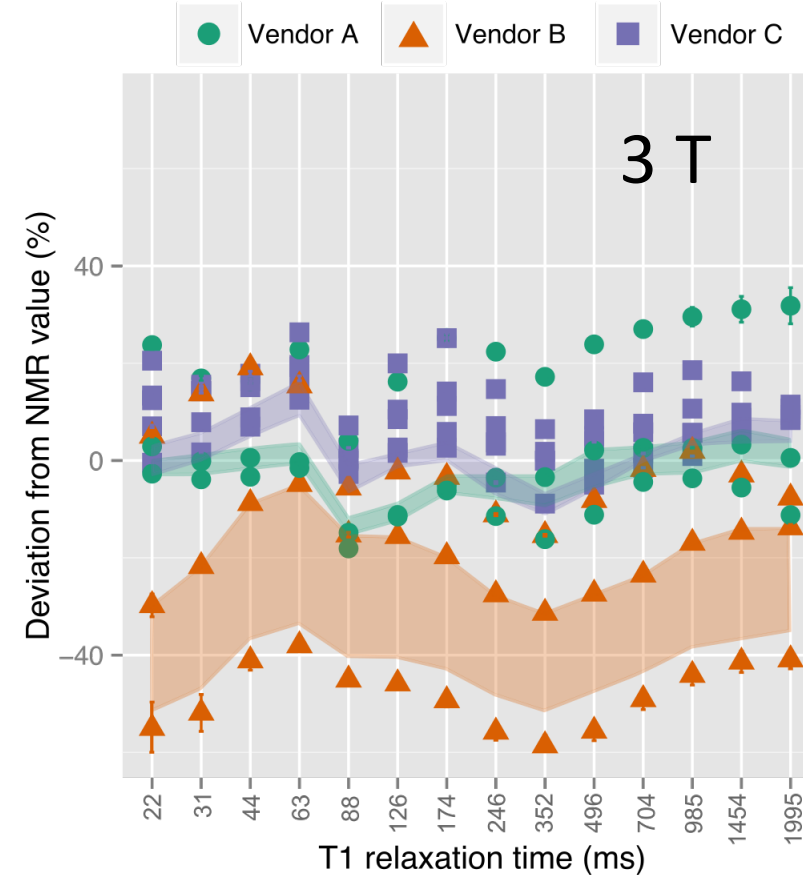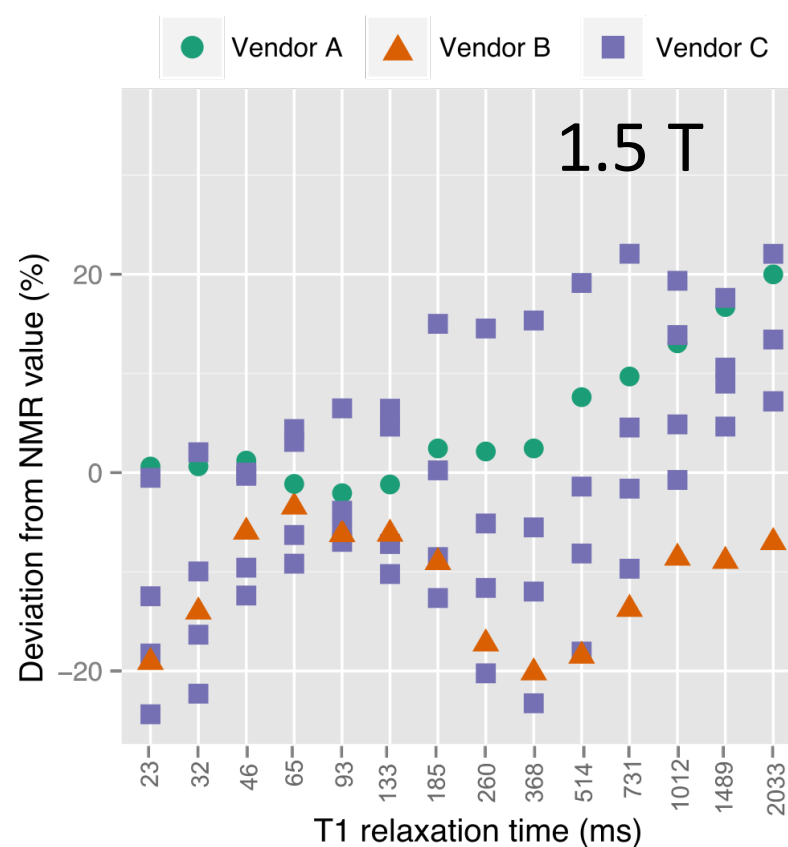# Inversion Recovery: MRI comparison to NMR measured values
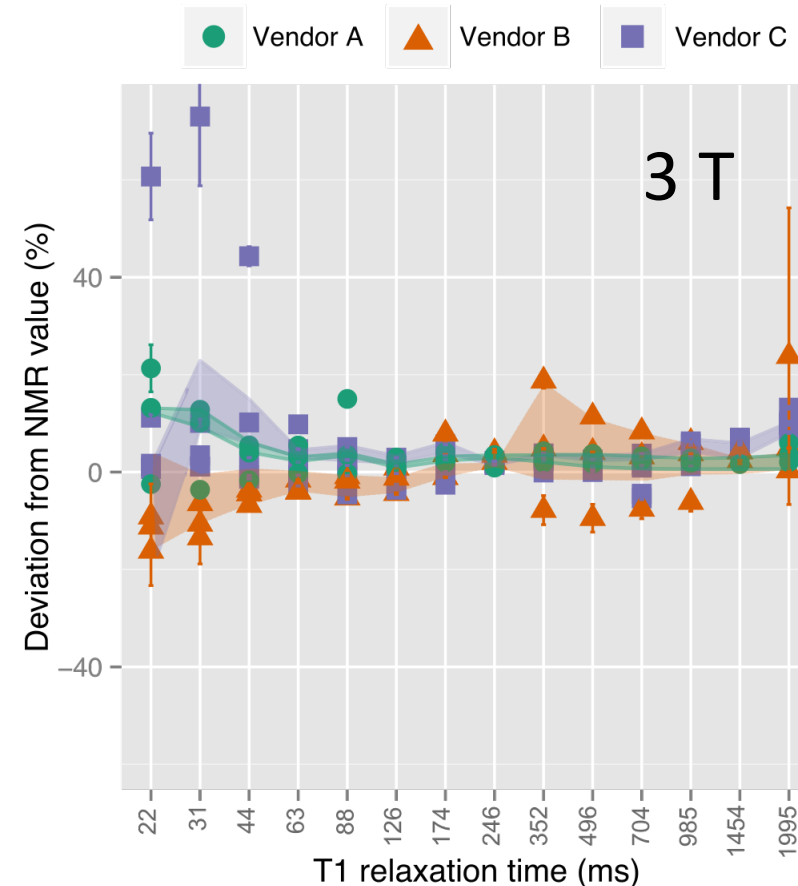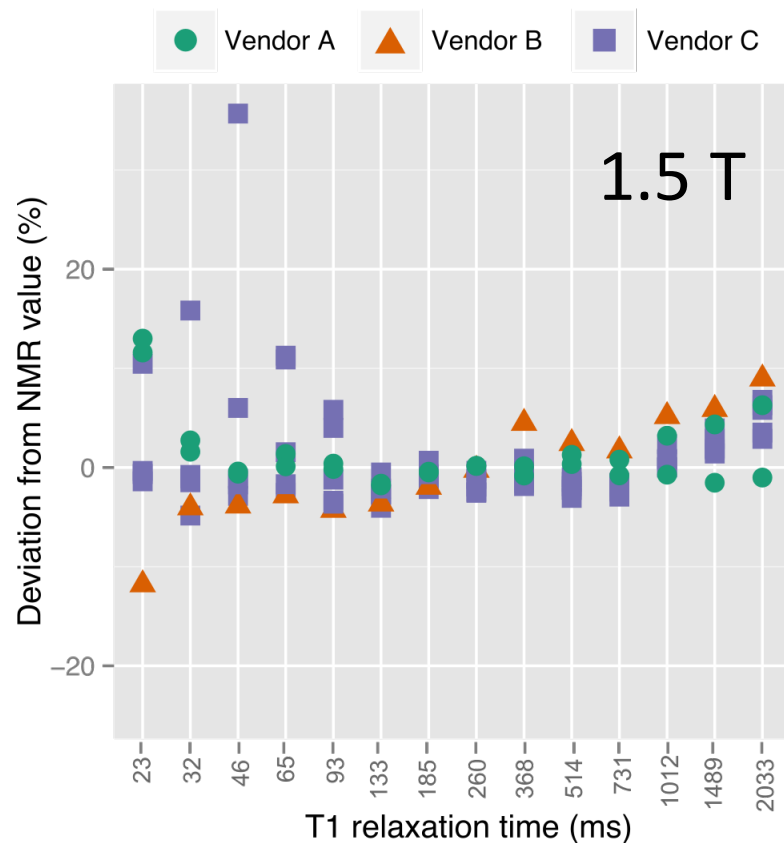
Note: 3 T y-axis range is 2x the 1.5 T y-axis range.

Colored bands show the range of values at a single repeatability site.

Overall, Inversion Recovery is accurate.
Difficulty fitting short T1 times likely due to selected inversion times.

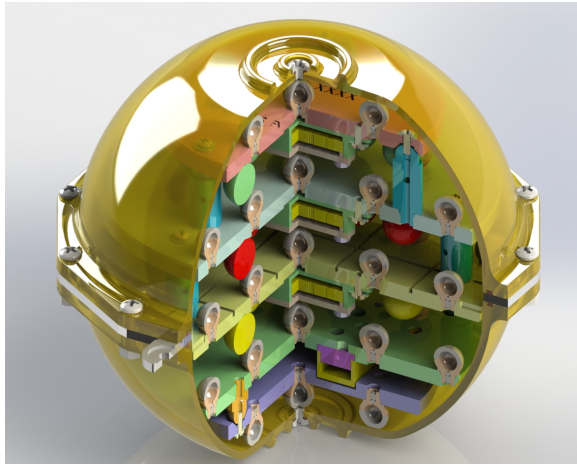# Variable Flip Angle: MRI comparison to NMR measured values

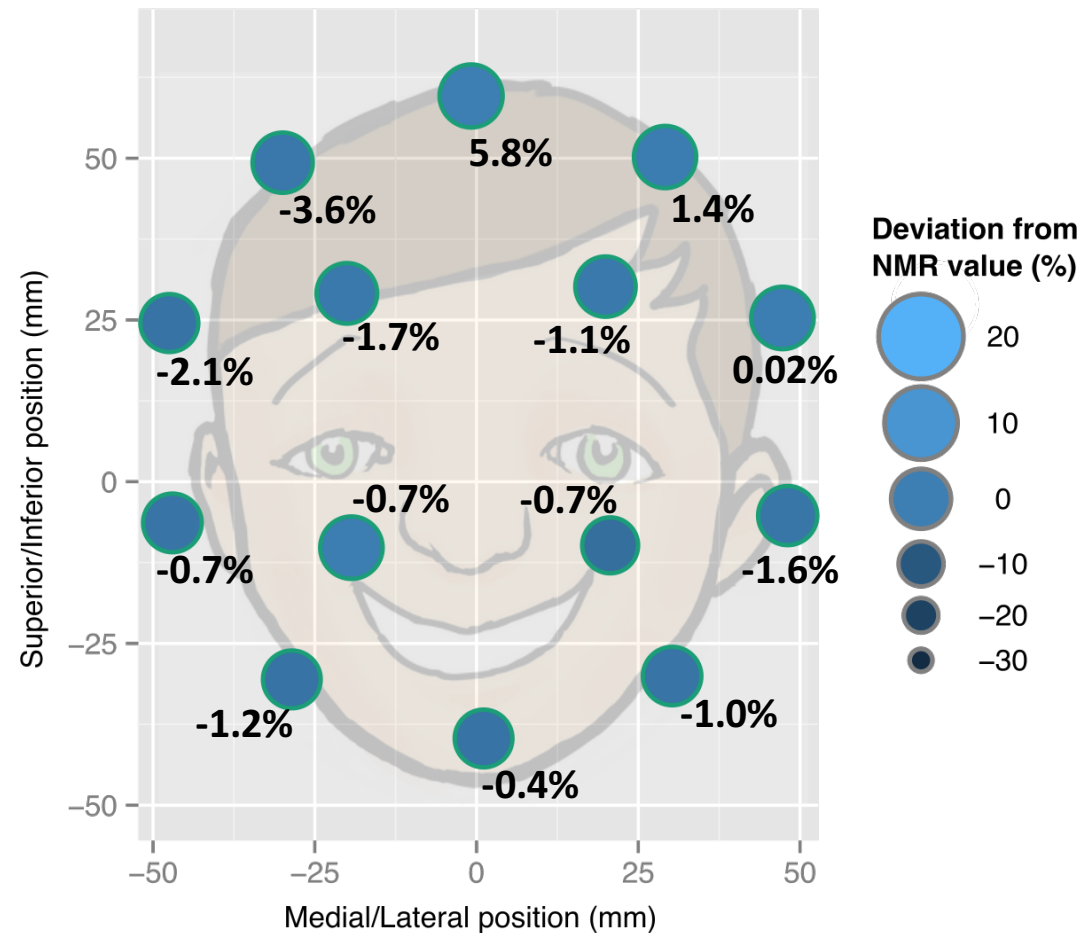Note: 3 T y-axis range is 2x the 1.5 T y-axis range.

Colored bands show the range of values at a single repeatability site.

Can we understand the systematic patterns in the 3 T data?

Spatial dependence of variations: Inversion Recovery

Inversion Recovery, 1.5 T data from Vendor A

Deviation from NMR values ranges from -3.6 to 5.8 %

Spatial dependence of variations: Inversion Recovery

1.5 T

3 T

Scanner, Method
- Vendor A; IR
- Vendor B; IR
- Vendor C; IR

Deviation from NMR value (%)
20
10
0
−10
−20
−30
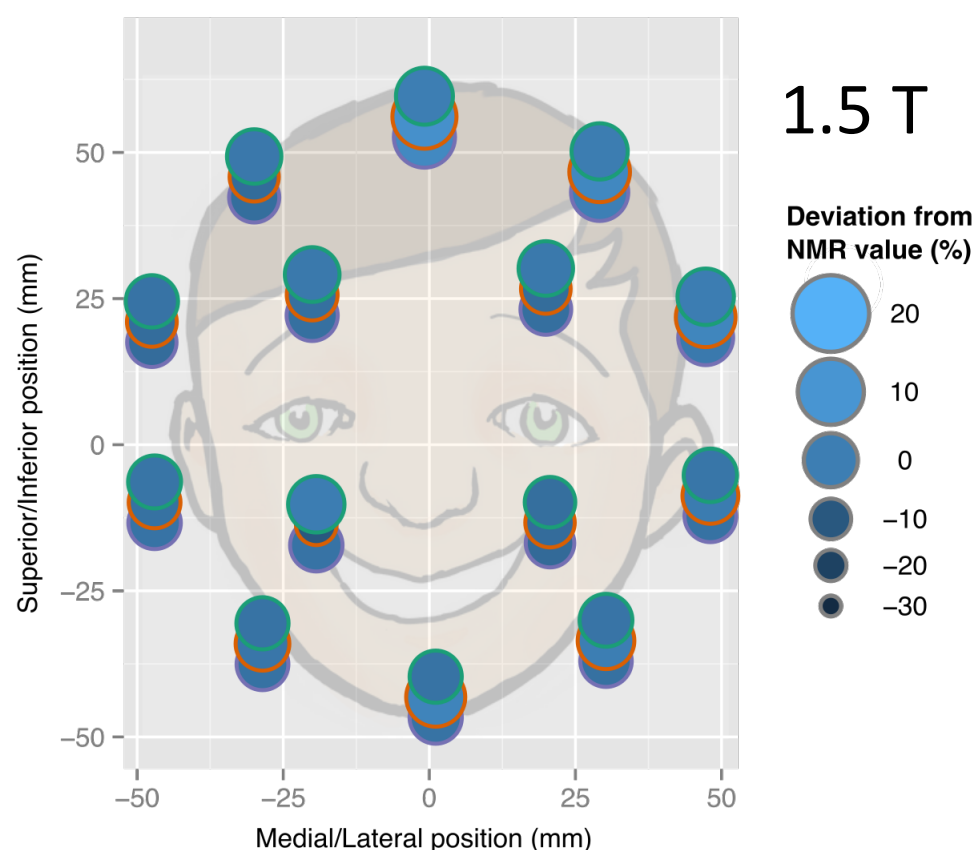
Vendor A deviation: -3.6 to 5.8 %
Vendor B deviation: -11.8 to 8.9 %
Vendor C deviation: -4.8 to 6.3 %
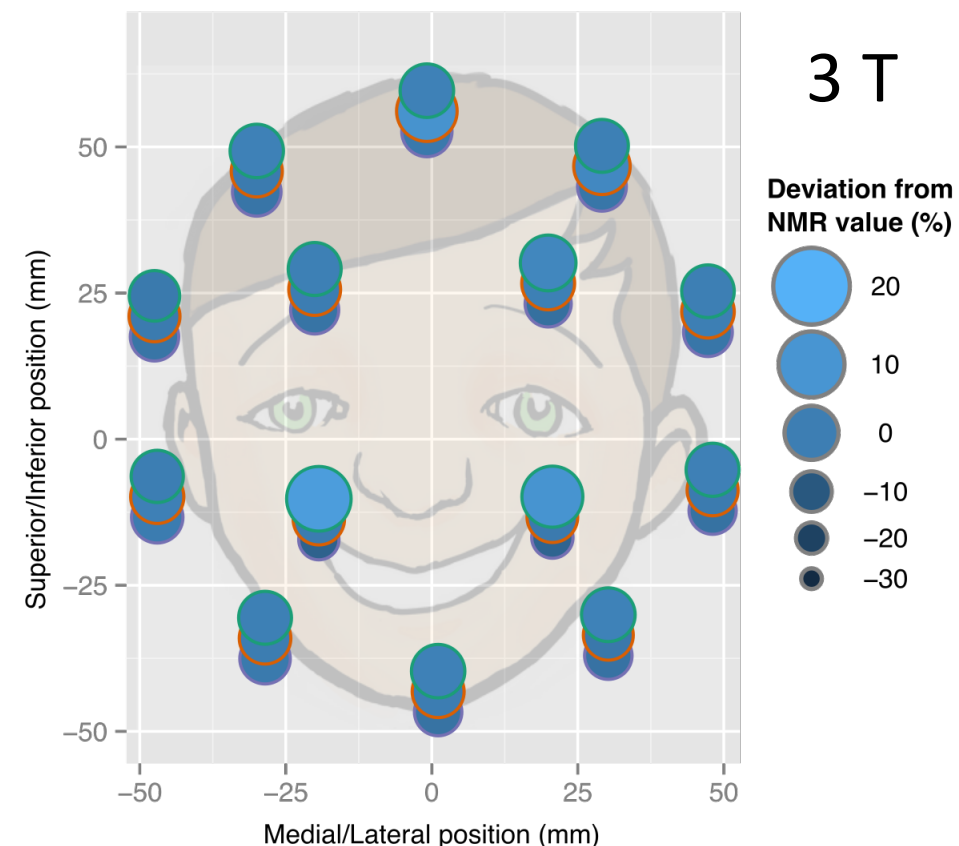
Vendor A deviation: 0.9 to 13.2 %
Vendor B deviation: -8.0 to 1.7 %
Vendor C deviation: 0.4 to 9.7 %

Spatial dependence of variations: Variable Flip Angle

1.5 T

3 T

There is spatial variation, and it is different for each system.
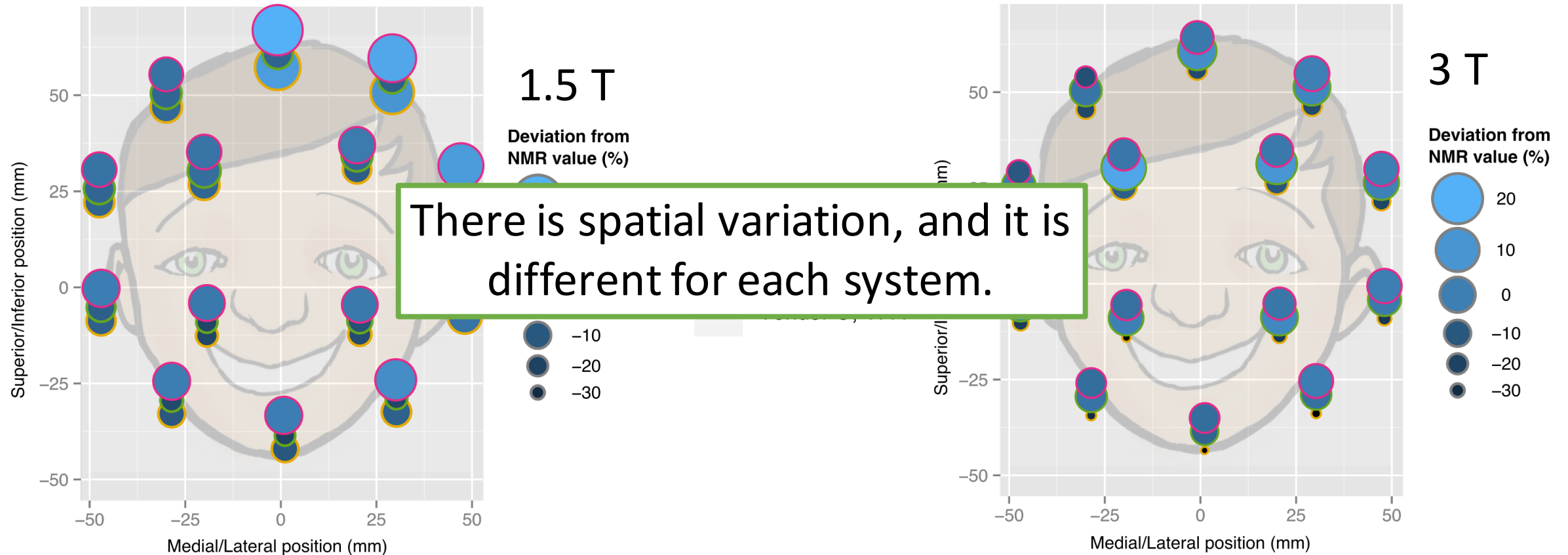
Vendor A deviation: -2.1 to 20.0 %
Vendor B deviation: -20.2 to -3.4 %
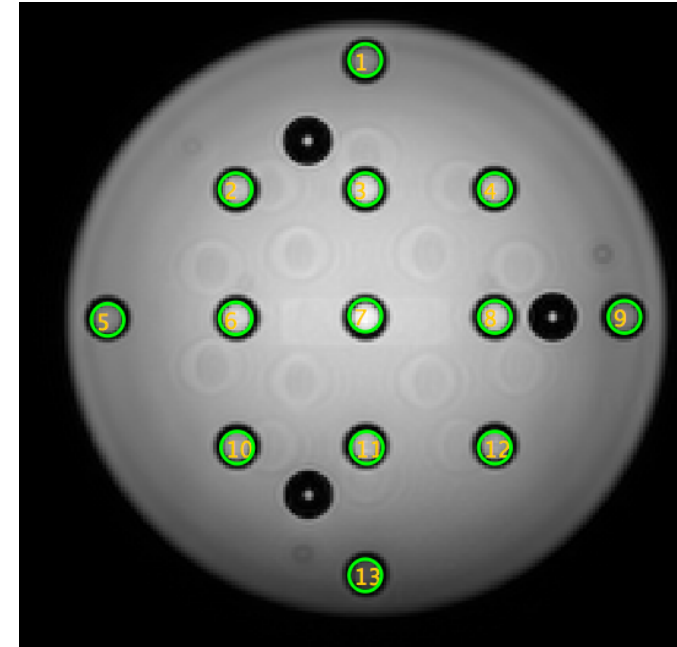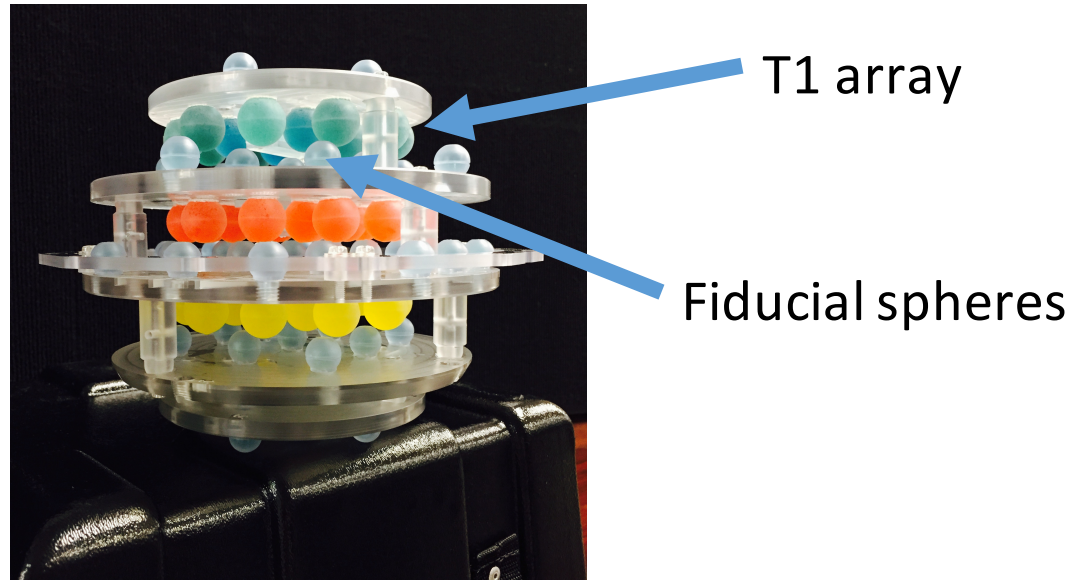**Vendor C deviation: -18.2 to 13.4 %**

Vendor A deviation: -14.8 to 3.3 %
Vendor B deviation: -33.3 to -8.8 %
Vendor C deviation: -6.6 to 16.3 %

Spatial dependence of variations: **Fiducial Sphere Plane**

T1 array

Fiducial spheres

Fiducial spheres are located below the T1 array, within the 3D VFA imaging section.
Fiducial spheres all contain the same concentration of $CuSO_4$.

Spatial dependence of variations: Variable Flip Angle

1.5 T

3 T
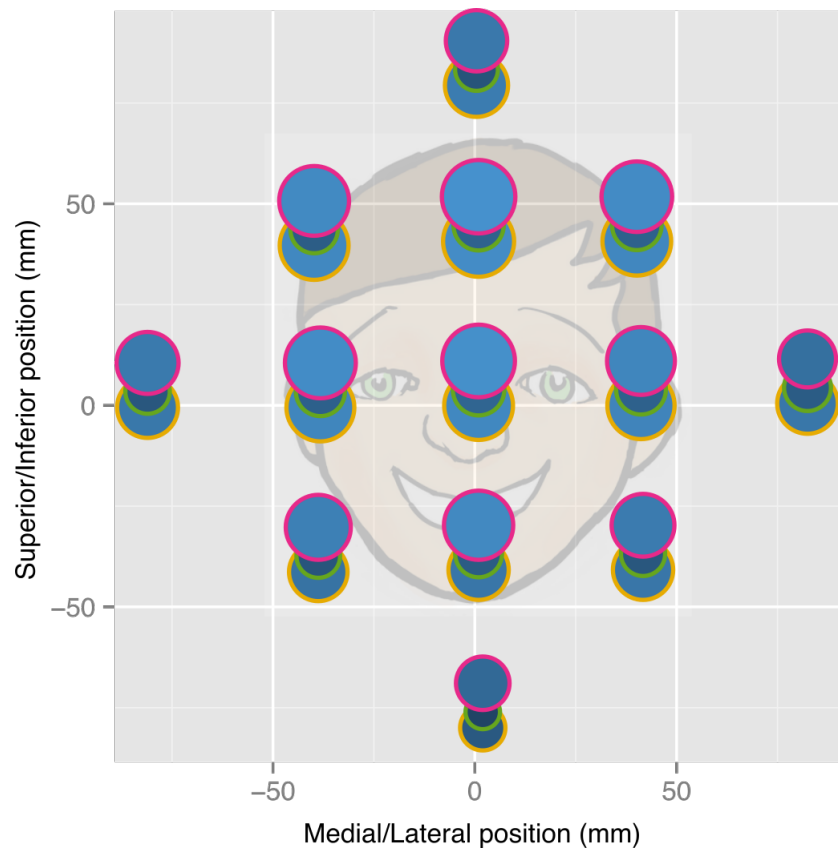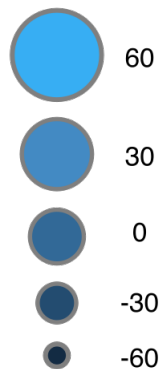
CuSO$_4$ is more temperature sensitive than NiCl$_2$, which affects our ability to interpret these results.

Vendor A deviation: -0.7 to 37.3 %
Vendor B deviation: -37.1 to -4.7 %
Vendor C deviation: -16.6 to 32.4 %
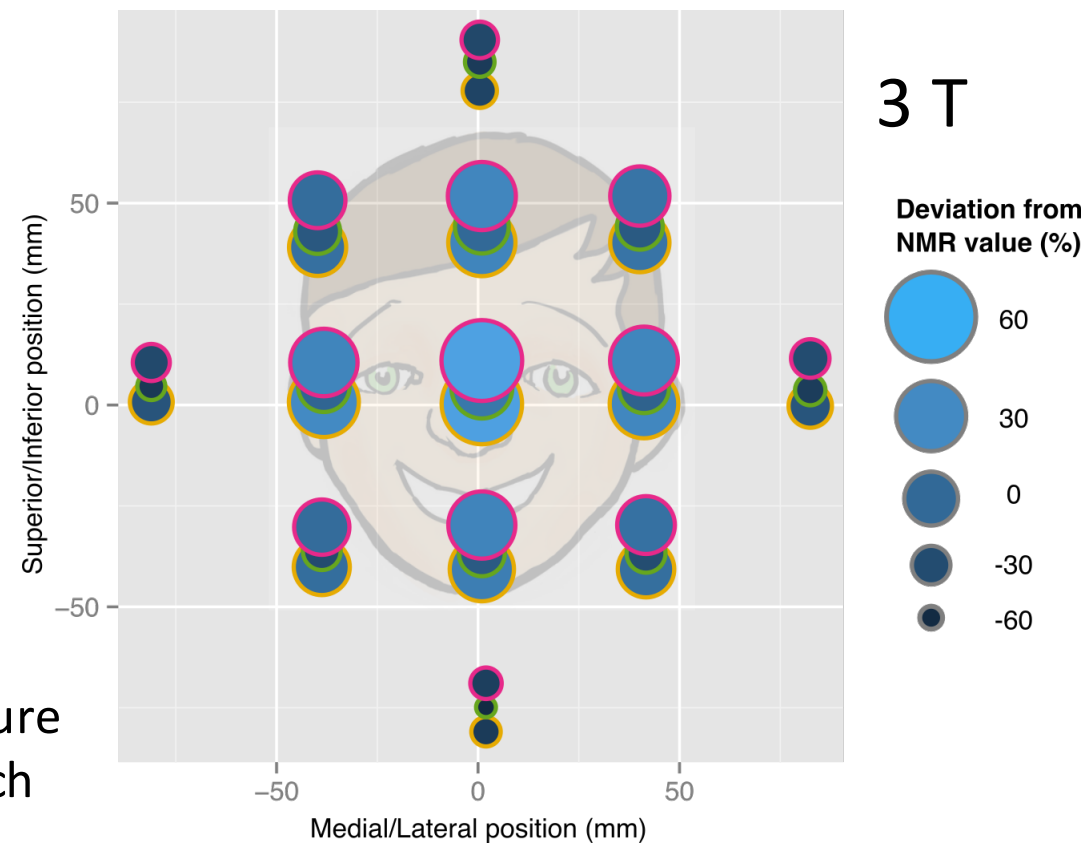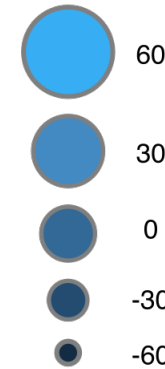
Vendor A deviation: -42.9 to 51.2 %
Vendor B deviation: -65.0 to -13.2 %
Vendor C deviation: -46.7 to 50.7 %

Why the deviation from known values?

- NMR methods v. MRI methods

- Temperature sensitivity over the reported temperatures
  - Non-linear, increases by 7.2% over the range of reported temperatures
  - *Deviation from reference T1 cannot be attributed only to temperature*

- Best efforts for similar protocol, but B1 pulse profiles unknown and could change across range of flip angles

- NMR deviation patterns suggest possible B1 effect

Multi-site, multi-vendor T1 variation

- T1 variations from NMR-measured value are correlated site-to-site within a vendor and by position within the head coil

- ISMRM/NIST system phantom is an excellent tool for evaluation multi-site acquisition protocols
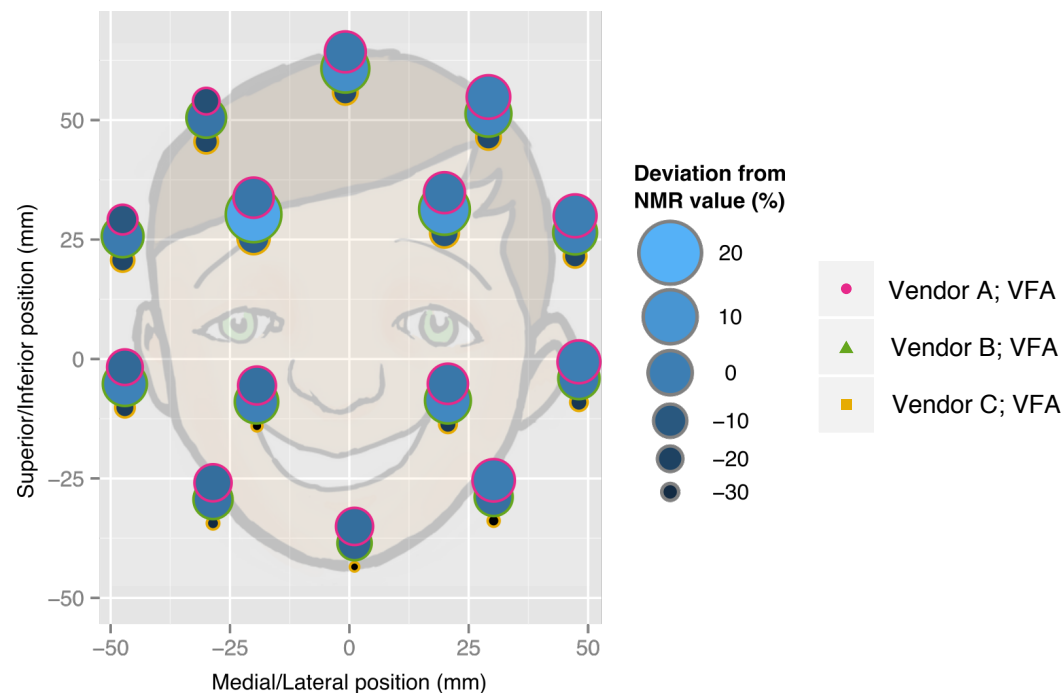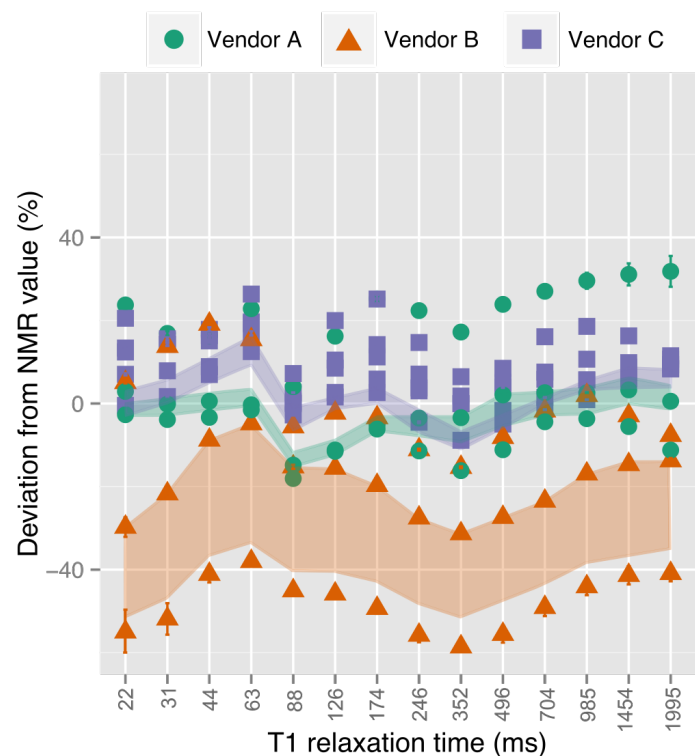
Acknowledgments

- We appreciate the efforts of all those who completed the scans of the phantom, especially when we asked them to repeat their efforts.

- We thank the SQMR committee past and present. Current members of the SQMR committee are:

For more information on NIST phantoms in development, the NIST/ISMRM phantom and to provide input, please visit:

http://collaborate.nist.gov/mriphantoms

To contact the author:

kathryn [dot] keenan [at] nist [dot] gov

NIST

ISMRM ONE COMMUNITY FOR CLINICIANS AND SCIENTISTS

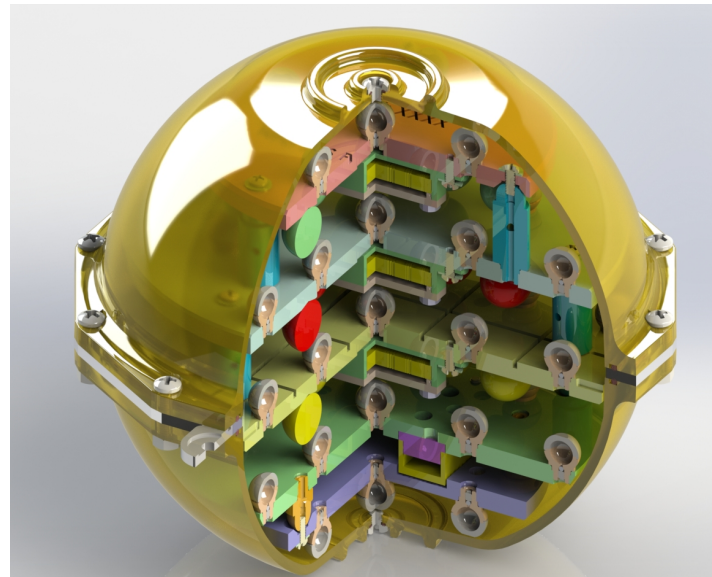# Reference Measurements: 1.5 T NMR

T1 array

Sample Name	Nominal Concentration, $NiCl_2$ (± 5%, mM)	T_1 (ms)	T_1 Standard Deviation, SD_{3R} (ms)	T_2 (ms)	T_2 Standard Deviation, SD_{3R} (ms)
T1-1	0.299	2 033	4.6	1 669	0.5
T1-2	0.623	1 489	1.4	1 244	0.6
T1-3	1.072	1 012	0.2	859.3	0.17
T1-4	1.720	730.8	1.10	628.5	0.13
T1-5	2.617	514.1	0.06	446.3	0.11
T1-6	3.912	367.9	0.66	321.2	0.30
T1-7	5.731	260.1	0.04	227.7	0.07
T1-8	8.297	184.6	0.02	161.9	0.06
T1-9	11.936	132.7	0.02	117.1	0.03
T1-10	17.070	92.7	0.09	81.9	0.02
T1-11	24.326	65.4	0.10	57.7	0.02
T1-12	34.590	46.32	0.010	41.0	0.01
T1-13	49.122	32.45	0.012	28.7	0.03
T1-14	69.680	22.859	0.043 7	20.2	0.01

T2 array

Sample Name	Nominal Concentration, $MnCl_2$ (± 5%, mM)	T_1 (ms)	T_1 Standard Deviation, SD_{3R} (ms)	T_2 (ms)	T_2 Standard Deviation, SD_{3R} (ms)
T2-1	0.013	2 376	2.2	939.4	1.11
T2-2	0.021	2 183	1.2	594.3	0.32
T2-3	0.031	1 870	6.0	416.5	1.13
T2-4	0.047	1 539	3.8	267.0	0.11
T2-5	0.069	1 237	0.4	184.9	0.11
T2-6	0.101	1 030	1.7	140.6	0.05
T2-7	0.145	752.2	1.12	91.76	0.029
T2-8	0.207	550.2	0.18	64.84	0.029
T2-9	0.296	413.4	0.29	45.28	0.029
T2-10	0.421	292.9	0.15	30.62	0.014
T2-11	0.599	194.9	0.08	19.76	0.017
T2-12	0.849	160.2	0.23	15.99	0.012
T2-13	1.104	106.4	0.02	10.47	0.006
T2-14	1.704	83.33	0.10	8.15	0.011

Aliquots of each solution were sealed into 2 mm outside diameter (OD) quartz ($NiCl_2$ solutions) or 3 mm (OD) PTFE ($MnCl_2$ solutions) NMR tubes. Quartz samples were sealed using a methane/oxygen torch to flame seal. PTFE samplers were sealed with a PTFE plug inserted 1 cm into the sample tube. A fiber optic temperature probe was positioned with the sensor in the middle of the radiofrequency (RF) coil. Each sample was equilibrated to 293.00 K (conditions noted below) for a minimum of 15 minutes. Samples were shimmed using the Berger-Braun shimming method prior to collecting relaxation time data.

NMR details of NMR-IR experiments can be found in: *200 and More NMR Experiments: A Practical Course, S. Berger & S. Braun*, ISBN-13: 978-3527310678.

NMR details of NMR-CPMG experiments can be found in: *200 and More NMR Experiments: A Practical Course, S. Berger & S. Braun*, ISBN-13: 978-3527310678.

Reference Measurements: 3 T NMR

T1 array

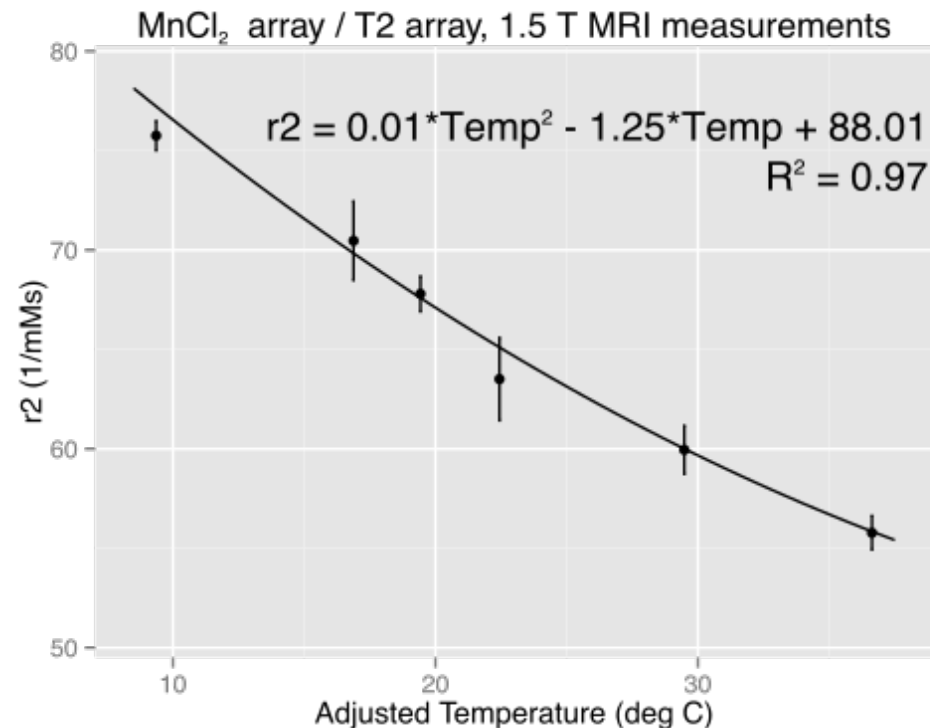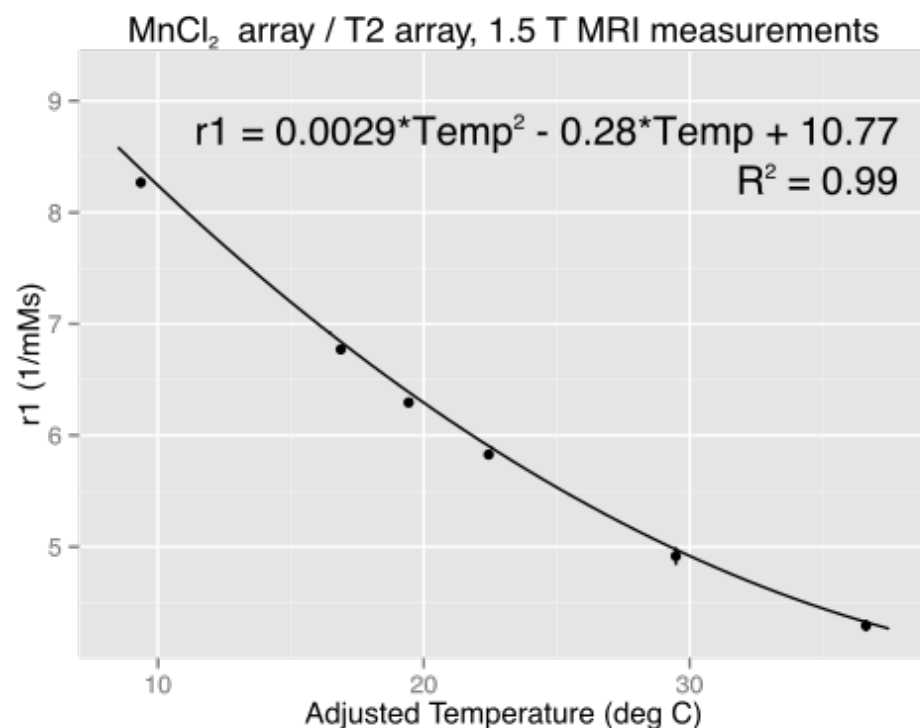| Sample Name	Nominal Concentration, NiCl$_2$ ($\pm$ 5%, mM)	T$_1$ (ms)	T$_1$ Standard Deviation, SD$_{3R}$ (ms)	T$_2$ (ms)	T$_2$ Standard Deviation, SD$_{3R}$ (ms)
T1-1	0.299	1 989	1.0	1 465	1.0
T1-2	0.623	1 454	2.5	1 076	1.8
T1-3	1.072	984.1	0.33	717.9	1.12
T1-4	1.720	706	1.5	510.1	1.36
T1-5	2.617	496.7	0.41	359.6	0.22
T1-6	3.912	351.5	0.91	255.5	0.07
T1-7	5.731	247.13	0.086	180.8	0.04
T1-8	8.297	175.3	0.11	127.3	0.14
T1-9	11.936	125.9	0.33	90.3	0.14
T1-10	17.070	89.0	0.17	64.3	0.05
T1-11	24.326	62.7	0.13	45.7	0.12
T1-12	34.590	44.53	0.090	31.86	0.02
T1-13	49.122	30.84	0.016	22.38	0.02
T1-14	69.680	21.719	0.005 4	15.83	0.03

T2 array

Sample Name	Nominal Concentration, MnCl$_2$ ($\pm$ 5%, mM)	T$_1$ (ms)	T$_1$ Standard Deviation, SD$_{3R}$ (ms)	T$_2$ (ms)	T$_2$ Standard Deviation, SD$_{3R}$ (ms)
T2-1	0.013	2 480	10.8	581.3	0.39
T2-2	0.021	2 173	14.7	403.5	0.55
T2-3	0.031	1 907	10.3	278.1	0.28
T2-4	0.047	1 604	7.2	190.94	0.011
T2-5	0.069	1 332	0.8	133.27	0.073
T2-6	0.101	1 044	3.2	96.89	0.049
T2-7	0.145	801.7	1.70	64.07	0.034
T2-8	0.207	608.6	1.03	46.42	0.014
T2-9	0.296	458.4	0.33	31.97	0.083
T2-10	0.421	336.5	0.18	22.56	0.012
T2-11	0.599	244.2	0.09	15.813	0.006 1
T2-12	0.849	176.6	0.09	11.237	0.005 7
T2-13	1.104	126.9	0.03	7.911	0.003 7
T2-14	1.704	90.9	0.05	5.592	0.005 5

Aliquots of each solution were sealed into 2 mm outside diameter (OD) quartz (NiCl$_2$ solutions) or 3 mm (OD) PTFE (MnCl$_2$ solutions) NMR tubes. Quartz samples were sealed using a methane/oxygen torch to flame seal. PTFE samplers were sealed with a PTFE plug inserted 1 cm into the sample tube. A fiber optic temperature probe was positioned with the sensor in the middle of the radiofrequency (RF) coil. Each sample was equilibrated to 293.00 K (conditions noted below) for a minimum of 15 minutes. Samples were shimmed using the Berger-Braun shimming method prior to collecting relaxation time data.

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Reference Measurements: temperature dependence

MnCl$_2$ array / T2 array, 1.5 T MRI measurements

$$r1 = 0.0029*Temp^2 - 0.28*Temp + 10.77$$
$$R^2 = 0.99$$

r1 (1/mMs)

Adjusted Temperature (deg C)

MnCl$_2$ array / T2 array, 1.5 T MRI measurements

$$r2 = 0.01*Temp^2 - 1.25*Temp + 88.01$$
$$R^2 = 0.97$$

r2 (1/mMs)
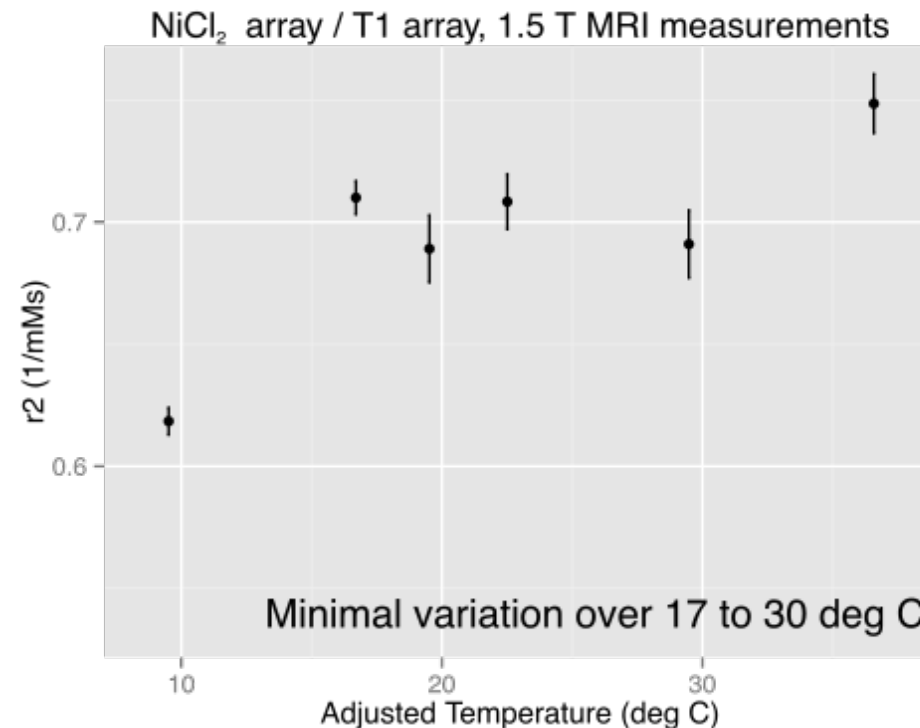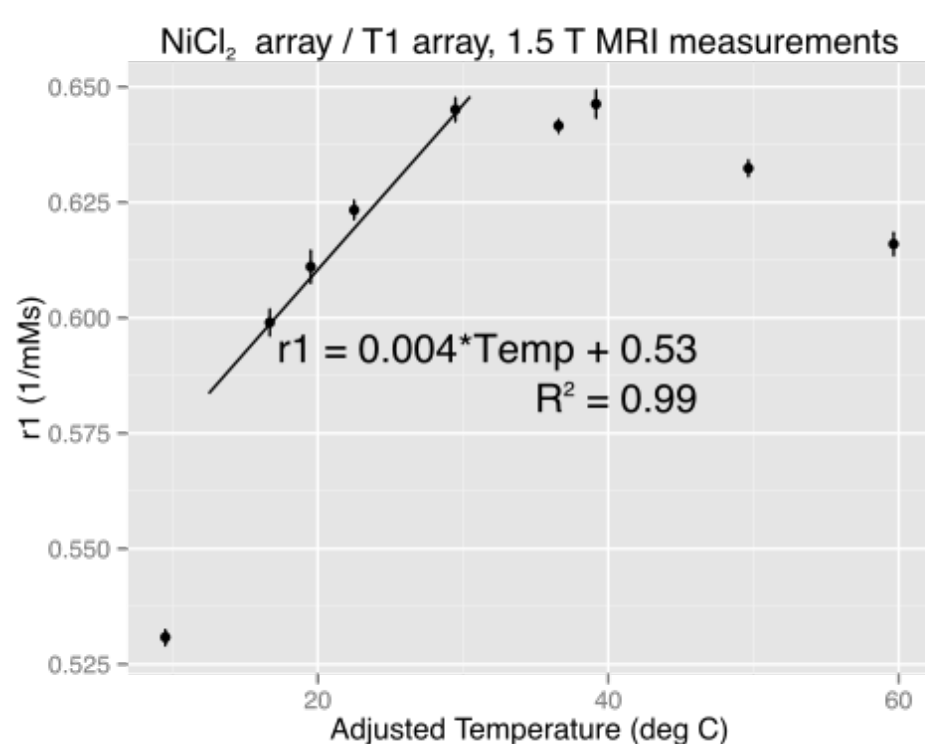
Adjusted Temperature (deg C)

Preliminary assessment of temperature dependence
Sample spheres, the same as those used in the commercial phantoms, were imaged on a 1.5 T small-bore system. A temperature-control system was used with a fiber-optic probe to achieve temperatures of approximately 10, 17, 20, 23, 30 and 37 °C.
Inversion recovery spin-echo was used to measure T1 relaxation time with: TR = 10 s, TE = 20 ms, TI = 50, 75, 100, 125, 150, 250, 500, 1000, 1500, 2000 and 3000 ms.
Spin echo was used to measure T2 relaxation time with: TR = 10 s, TE = 15, 20, 40, 80, 160, and 320 ms.

Reference Measurements: temperature dependence

NiCl₂ array / T1 array, 1.5 T MRI measurements

$$r1 = 0.004*Temp + 0.53$$
$$R^2 = 0.99$$

NiCl₂ array / T1 array, 1.5 T MRI measurements

Minimal variation over 17 to 30 deg C

Preliminary assessment of temperature dependence
Sample spheres, the same as those used in the commercial phantoms, were imaged on a 1.5 T small-bore system. A temperature-control system was used with a fiber-optic probe to achieve temperatures of approximately 10, 17, 20, 23, 30 and 37 °C.
Inversion recovery spin-echo was used to measure T1 relaxation time with: TR = 10 s, TE = 20 ms, TI = 50, 75, 100, 125, 150, 250, 500, 1000, 1500, 2000 and 3000 ms.
Spin echo was used to measure T2 relaxation time with: TR = 10 s, TE = 15, 20, 40, 80, 160, and 320 ms.