Rev A

qCal-MR™ Premium System Phantom Protocols for Scanner Set-Up

The CMRI Premium System Phantom Protocol performs analysis of the T_1, T_2, Proton Density, and Geometric Distortion features of the system phantom. Phantom temperature is determined by analyzing the LC Thermometer in the isotopic volume scans used for the geometric distortion calculations. The input to this protocol should be a single study that contains all of the relevent scans.

For specific guidance on phantom preparation, image acquisition, and expected scanner parameters, please review the appropriate manual.

Liquid Crystal (LC) Thermometer Sequence

Requirements
Across all series, there shall be a **single value** for **field of view mm**.
Across all series, there shall be a **single value** for **pixel bandwidth**.
Across all series, there shall be a **single value** for **repetition time**.
Across all series, there shall be a **single value** for **b value**.
Across all series, there shall be a **single value** for **echo time**.
Across all series, there shall be a **single value** for **inversion time**.
Fat suppression shall be **False**.
Repetition time shall be **at most 25**.
Slices shall be **at least 100**.
Across all series, there shall be a **single value** for **flip angle**.

Expected Parameters
B value should be **0**.
Flip angle should be between **10 and 20**.
Repetition time should be between **4 and 10**.
Slice thickness should be **0.9 and 1.1.**.

Geometric Distortion Sequence

Requirements
Across all series, there shall be a **single value** for **field of view mm**.
Across all series, there shall be a **single value** for **pixel bandwidth**.
Number of frames (series * temporal positions) shall be 1.
Across all series, there shall be a **single value** for **repetition time**.
Across all series, there shall be a **single value** for **flip angle**.
Across all series, there shall be a **single value** for **b value**.
Across all series, there shall be a **single value** for **echo time**.
Across all series, there shall be a **single value** for **inversion time**.
Fat suppression shall be **False**.
Repetition time shall be **at most 2000**.
Slices shall be **at least 100**.

Expected Parameters
B value should be **0**.
Flip angle should be **10**.
Repetition time should be **at most 4**.
Slice thickness should be **0.9 and 1.1.**.

T_1 VFA Sequence

Requirements
Across all series, there shall be a **single value** for **field of view mm**.
Across all series, there shall be a **single value** for **pixel bandwidth**.
Across all series, there shall be a **single value** for **repetition time**.
Across all series, there shall be a **single value** for **echo time**.
Across all series, there shall be a **single value** for **inversion time**.
Across all series, there shall be a **single value** for **b value**.
All values for **parameter flip angle** shall be **unique, without duplicates**.
Repetition time shall be **at most 2000**.
Across all series, there shall be **at least 2 distinct values** for **flip angle**.

Expected Parameters
B value should be **0**.
Flip angle should be **2, 5, 10, 15, 20, 25, 30**.
Fat suppression should be **False**.
Repetition time should be **at most 10**.
Echo time should be **at most 2.5**.
Slice thickness should be **at most 3**.
Echo time should be **at most 3**.

T_1 VTI Sequence

Requirements
Across all series, there shall be a **single value** for **field of view mm**.
Across all series, there shall be a **single value** for **pixel bandwidth**.
Across all series, there shall be a **single value** for **repetition time**.
Across all series, there shall be a **single value** for **flip angle**.
Across all series, there shall be a **single value** for **b value**.
Across all series, there shall be a **single value** for **echo time**.
Fat suppression shall be **False**.
Repetition time shall be **at least 2000**.
Inversion time shall not be **null**.
Across all series, there shall be **at least 2 distinct values** for **inversion time**.

Expected Parameters
B value should be **0**.
Repetition time should be **4500**.
Echo time should be **at most 7.6**.
Slice thickness should be **6**.
Inversion times should be **35 (or 50 on a GE scanner), 75, 100, 125, 150, 250, 1000, 1500, 2000, 3000**.

T_2 Sequence

Requirements
Across all series, there shall be a **single value** for **field of view mm**.
Across all series, there shall be a **single value** for **pixel bandwidth**.
Across all series, there shall be a **single value** for **repetition time**.
Across all series, there shall be a **single value** for **flip angle**.
Across all series, there shall be a **single value** for **b value**.
Across all series, there shall be a **single value** for **inversion time**.
Fat suppression shall be **False**.
Repetition time shall be **at least 2000**.
Across all series, there shall be **at least 4 distinct values** for **echo time**.

Expected Parameters
Repetition time should be **5000**.
Echo times should be **15, 30, 45, 60, 25, 50, 75, 100, 40, 80, 120, 160 for GE; 16 values incrementing by 11 for Philips; or 32 values incrementing by 10 for Siemens scanners**.

SNR Sequence

Requirements
Across all series, there shall be a **single value** for **field of view mm**.
Across all series, there shall be a **single value** for **pixel bandwidth**.
Across all series, there shall be a **single value** for **repetition time**.
Across all series, there shall be a **single value** for **flip angle**.
Across all series, there shall be a **single value** for **b value**.
Across all series, there shall be a **single value** for **echo time**.
Fat suppression shall be **False**.
Repetition time shall be **at least 2000**.
Echo time shall be **at most 24**.
Flip angle shall be **at most 90**.
Slice thickness shall be **at most 10**.
Inversion time shall be any of **[None, 0]**.
Number of frames (series * temporal positions) shall be **2**.

Expected Parameters
All series should be in immediate succession.
B value should be **0**.
Echo time should be **10**.
Repetition time should be **5000**.
Slice thickness should be **6**.

Proton Density Sequence

Requirements
Across all series, there shall be a **single value** for **field of view mm**.
Across all series, there shall be a **single value** for **pixel bandwidth**.
Number of series shall be **1**.
Across all series, there shall be a **single value** for **repetition time**.
Across all series, there shall be a **single value** for **flip angle**.
Across all series, there shall be a **single value** for **b value**.
Across all series, there shall be a **single value** for **echo time**.
Fat suppression shall be **False**.
Repetition time shall be **at least 2000**.
Echo time shall be **at most 24**.
Flip angle shall be **at most 90**.
Inversion time shall be any of **[None, 0]**.

Expected Parameters
B value should be **0**.
Echo time should be **10**.
Repetition time should be **5000**.
Slice thickness should be **6**.

LC Thermometer qCal-MR™ Calculation Info

Identify the location of the LC thermometer and use the phase of the vials to determine temperature.

Geometric Distortion qCal-MR™ Calculation Info

Geometric distortion metrics are reported as described in **A standard system phantom for magnetic resonance imaging (Stupic, Karl F et al., Magnetic resonance in medicine vol. 86,3 (2021): 1194-1211. doi:10.1002/mrm.28779)**.

The specific process for determining geometric distortion used by qCal-MR™ is as follows:

› Identify the approximate center of each fiducial sphere using the typical qCal-MR™ VOI finding algorithm.

› Enlarge the volume surrounding the approximate center, and identify a more accurate center using a modified version of the Hough circle transform designed to work in three dimensions.

› With the center sphere as the origin, use Procrustes analys to determine the rotation between the actual positions and the measured positions that minimizes their difference.

› Use a linear least-squares fit to determine the scale factor that minimizes the difference between the measured and physical geometry.

Distortion is measured as $R_{measured} - R_{expected}$, where R is the distance from the center sphere after translation, rotation, and scaling have taken place.

T_1 VFA qCal-MR™ Calculation Info

The T_1 estimation is taken from **"T1 Estimation from SSI Measurements at Multiple Flip Angles" in Magnetic Resonance Imaging: Physical Principles and Sequence Design.**

In this calculation, the signal-α space is transformed into x-y space using:

$x(\alpha) = signal(\alpha) / \tan(\alpha)$, and
$y(\alpha) = signal(\alpha) / \sin(\alpha)$

In this space, the points form a straight line with slope E_1 and:

$E1 = e^{(-TR/T1)}$
where TR is the repetition time of the scan. T_1 is calculated from this relationship using a linear least squares fit.

T_1 VTI qCal-MR™ Calculation Info

The T_1 value is estimated by performing a non-linear least-squares fit to the following equation:

$$S(TI) = M0 * abs(1 - (1 + \delta)* e^{-TI/T1} + e^{-TR/T1})$$

With:

S(TI) = Measured signal intensity at inversion time TI
M0 = Magnitude of response at full relaxation
δ = Inversion efficiency factor
TI = Inversion Time (ms)
TR = Repetition Time (ms)
T1 = T_1 Value (ms)

T_2 qCal-MR™ Calculation Info

T_2 is calculated as described in **A standard system phantom for magnetic resonance imaging (Stupic, Karl F et al., Magnetic resonance in medicine vol. 86,3 (2021): 1194-1211. doi:10.1002/mrm.28779)**, according to the following equation:

$$S(TE) = S_0e^{-TE/T2} + c$$

Where S(TE) is the signal produced in response to a given echo time (TE) and c is a constant offset.

In practice, some scanners report poor quality values for lower echo times. In order to detect this, qCal-MR™ performs an evaluation of fit quality with the first few echo times either included or excluded (using a sample of 1% of the voxels). If the mean R^2 is below 0.9 with all echo times but above 0.9 with echo times excluded, the calculation will be performed with echo times excluded.

SNR qCal-MR™ Calculation Info

The Signal-to-Noise ratio calculation is performed according to **NEMA Standards Publication MS 1–2008 R2014 Determination of Signal-to-Noise Ratio SNR in Diagnostic MRI, method 1**.

The calculation requires exactly two images, and is defined as:

› Define a signal image as the mean value of the signal across both images, and a noise image as the the difference of the two images.

› For each VOI, define the signal as the mean value of voxels in the signal image and the noise as the standard deviation of the voxels in the noise image, divided by the square root of two.

› The SNR, then, is the ratio of the signal to the noise for each VOI.

Note that the displayed volume is the ratio of the signal image to the noise image per pixel. This is meant for visualization purposes only, and does not correspond exactly to the SNR calculations for each VOI.

Proton Density qCal-MR™ Calculation Info

Proton density metrics are calculated as described in **A standard system phantom for magnetic resonance imaging (Stupic, Karl F et al., Magnetic resonance in medicine vol. 86,3 (2021): 1194-1211. doi:10.1002/mrm.28779)**.

The MR proton density is calculated by:

› Determinng the local background by averaging the signal from seven or eight points taken outside the spheres and away from the LC Thermometer (background points are indicated in green in the visualization window).

› Normalizing each voxel by the local background from the closest sphere.

› Normalizing all voxels by the mean signal in the 100% water VOI.