User Manual

MRI-IQ-ETK: Digital **MRI** Test Phantoms and Automated **I**mage **Q**uality **E**valuation **T**ool**k**it for Assessing MRI Image Reconstruction Methods

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Food and Drug Administration

2025

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Summary

MRI-IQ-ETK is a software toolkit that generates three types of digital image quality (IQ) test phantoms in the continuous Fourier domain for assessing the performance of magnetic resonance imaging (MRI) image reconstruction methods. The software toolkit supports the evaluation of the following IQ metrics: geometric accuracy, intensity uniformity, percentage ghosting, sharpness, signal-to-noise ratio, high-contrast resolution, and low-contrast object detectability. This toolkit can be helpful for researchers working in the fields of medical imaging and image quality assessment in MRI.

This GitHub repository contains the open-source Python code for two major functions:

1. Digital phantom creation (digital_phantom.py): creating 3 types of phantoms in k-space: disk, resolution, low-contrast phantom
2. Metrics evaluation (evaluation_metrics.py): geometric accuracy, intensity uniformity, percentage ghosting, sharpness, SNR, high contrast resolution, and low contrast detectability.

The code has been used to support the paper entitled "*Evaluating Machine Learning-Based MRI Reconstruction Using Digital Image Quality Phantoms*" published in BioEngineering 2024 (https://doi.org/10.3390/bioengineering11060614). The code is also affiliated with the CDRH Regulatory Science Tool MRI-IQ-ETK (link to be inserted)

Disclaimer

Start Here

1. Install python 3.11.3 or any version greater

   (Note: the code was tested on python 3.11.3 and 3.11.5 by the authors but the user can check the compatibility with a lower version of python.)

2. Clone this repository and navigate to its root directory

   ```
   git clone https://github.com/DIDSR/mr-recon-eval-core.git
   ```

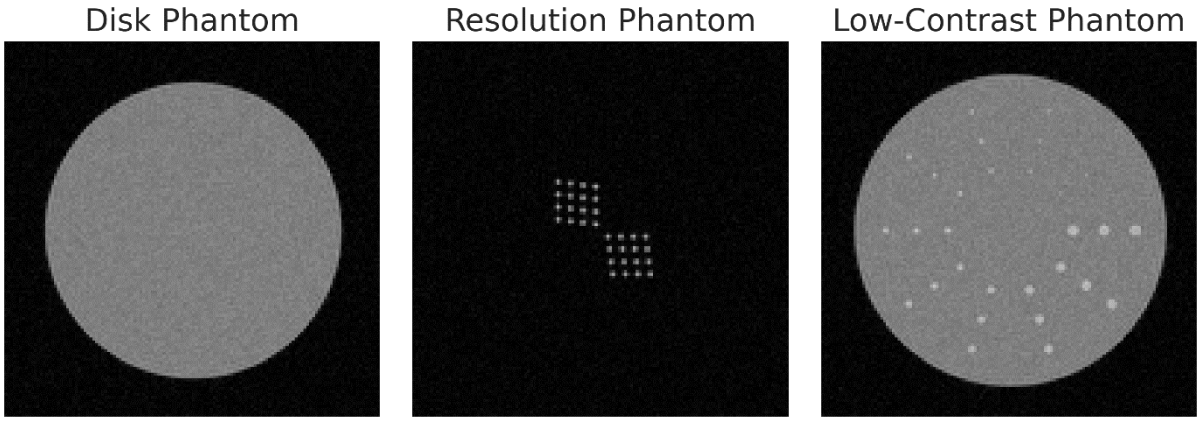
3. Install the required dependencies in a python environment

   ```
   pip install numpy matplotlib scikit-image scipy
   ```

Demo

Run `python demo.py`.

Expected Output




```
Geometric accuracy (maximum percentage error): 0.0003
Intensity uniformity: 94.2322
Percentage ghosting: 0.0009
Sharpness fwhm: 1.5268 Sharpness slope: 0.3233
SNR dual: 11.3576
High contrast resolution:
         number of resolved vertical lines in the upper resolution block:  4
         number of resolved horizontal lines in the lower resolution block:  4
Calculating low contrast detectability measurement (may take a while) ...
Low contrast detectability (number of complete spokes):  9
```

The exact values will be different in each run due to random noise in the generated phantom images. The evaluation result and the generated phantom images will be saved to an `output` folder.

How to Cite

- **Regulatory Science Tool (RST):** tbd
- **Paper:** Tan F, Delfino JG, Zeng R. Evaluating Machine Learning-Based MRI Reconstruction Using Digital Image Quality Phantoms. Bioengineering. 2024; 11(6):614. https://doi.org/10.3390/bioengineering11060614

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Appendix: Description of Functions

Key Functions I: Create Digital Phantom (digital_phantom.py)

Creates disk, resolution, low-contrast phantoms.

1. **disk_phantom**

Description: Creates a disk phantom.
Parameters:

- fov (tuple): Field of View (FOV) in millimeters (mm).
- radius (tuple): Circle radius in millimeters (mm).
- center (tuple, optional): Center coordinates of the disk in millimeters (mm). Default is (0,0).
- theta (float, optional): Rotation angle in degrees. Default is 0.
- matrix_size (tuple, optional): Matrix size in number of pixels. Default is (64,64).
- intensity (float, optional): Intensity of the disk. Default is 1.
- noise_std (float, optional): Standard deviation of complex Gaussian noise. Default is 0.

Returns:

- kspace (ndarray): Complex k-space representation of the disk.
- disk (ndarray): Image of the disk.

Reference: Digital_Reference_Objects GitHub repository

2. **resolution_phantom**

Description: Creates a resolution phantom.
Parameters:

- fov (tuple): Field of view in millimeters (mm).
- radius (tuple): Radii of individual holes in millimeters (mm).
- center (tuple, optional): Center of the phantom in millimeters (mm). Default is (0,0).
- array (tuple, optional): Number of holes in x,y dimension. Default is (4,4).
- matrix_size (tuple, optional): Matrix size of k-space & image. Default is (64,64).
- intensity (float, optional): Intensity of the image. Default is 1.
- noise_std (float, optional): Standard deviation of additive complex Gaussian noise. Default is 0.1.

Returns:

- kspace_res (ndarray): Complex k-space.
- res (ndarray): Image of resolution phantom.

3. **low_contrast_phantom**

Description: Creates a low contrast phantom.
Parameters:

- fov (tuple): Field of view in millimeters (mm).
- radius_range (tuple): Smallest and largest radii in millimeters (mm).
- center (tuple, optional): Center of the phantom in millimeters (mm). Default is (0,0).
- nspokes (int, optional): Number of spokes. Default is 10.
- spoke_dist (float, optional): Distance between phantoms within one spoke. Default is 20.
- disk_per_spoke (int, optional): Number of disks per spoke. Default is 3.
- matrix_size (tuple, optional): Matrix size. Default is (64,64).
- intensity (float, optional): Intensity of background phantom. Default is 1.

- contrast (float, optional): Additive intensity of the foreground phantoms. Default is 0.1.
- noise_std (float, optional): Noise standard deviation. Default is 0.1.

Returns:

- kspace_lc (ndarray): K-space of low contrast phantom.
- lc (ndarray): Image of low contrast phantom.

Key Functions II: Evaluation Metrics (evaluation_metrics.py)

Evaluate the essential metrics from the MRI images of disk, resolution, low-contrast phantoms.

4. geometric_accuracy

Description: Measure the geometric accuracy of a disk phantom.

Parameters:

- disk (ndarray): (M, N) Image to measure.
- fov (tuple): Field of view in millimeters (mm) (fov_x, fov_y).
- radius (tuple): Ground truth radius in millimeters (mm).
- center (tuple): Ground truth center in millimeters (mm).
- plot (bool, optional): Plot predicted axes, center, and bounding box. Default is False.

Returns:

- max_percentage_error (float): Maximum percentage error of major axis and minor axis compared with ground truth.
- eccentricity (float): Equals to 0 when input image is circle, range [0, 1).

5. intensity_uniformity

Description: Measure the intensity uniformity using a disk phantom.

Parameters:

- disk (ndarray): (M, N) Image to measure.
- fov (tuple): Field of view in millimeters (mm) (fov_x, fov_y).
- radius (tuple): Ground truth radius in millimeters (mm).
- center (tuple): Ground truth center in millimeters (mm).
- intensity (float): Ground truth intensity.
- plot (bool, optional): Plot predicted axes, center, and bounding box. Default is False.
- location_known (bool, optional): Consider the center of the disk known or unknown. Default is True. If known, use the known center to define ROI. If unknown, use thresholding to detect ROI.

Returns:

• intensity_bias (float): Intensity bias, percentage error of mean intensity compared with ground truth.
• intensity_uniform (float): Intensity uniformity.

6. percentage_ghosting

Description: Measure the percentage ghosting of a disk phantom.

Parameters:

- disk (ndarray): (M, N) Image to measure.
- fov (tuple): Field of view in millimeters (mm) (fov_x, fov_y).
- center (tuple): Ground truth center in millimeters (mm).
- intensity (float): Ground truth intensity.
- plot (bool, optional): Plot predicted axes, center, and bounding box. Default is False.

Returns:

- ghosting_ratio (float): Ghosting ratio, percentage image ghosting.

7. sharpness

Description: Sharpness using the edge spread function of a disk phantom.
Parameters:

- disk (ndarray): Disk image.
- fov (tuple): FOV of the disk.
- radius (tuple): Radius of the disk.
- center (tuple): Center of the disk.
- plot (bool, optional): Plot figures for debugging. Default is False.
- fit (bool, optional): Whether to fit the edge spread function to sigmoid. Default is False.

Returns:

- fwhm (float): Full-width-half-maximum of the fitted Lorentzian function.
- mal_val (float): Maximum value of the fitted Lorentzian function.

8. snr_dual_image

Description: SNR measurement using two disks.
Parameters:

- disk1 (ndarray): 1st disk phantom.
- disk2 (ndarray): 2nd disk phantom.
- fov (tuple): FOV of the disk phantoms in mm.
- radius (tuple): Radius of the disk phantoms in mm.
- center (tuple): Center of the disk phantoms in mm.
- plot (bool, optional): Plot for debugging. Default is False.
- signal_roi_width (int, optional): Signal ROI width. Default is 7.
- noise_roi_width (int, optional): Noise ROI width. Default is 13.

Returns:

- snr (float): SNR.

9. high_contrast_resolution

Description: High contrast resolution measurement using resolution phantom.
Parameters:

- res (ndarray): Image of resolution phantom.
- fov (tuple): Field of view in mm.
- radius (tuple): Radii of individual holes in mm.
- center (tuple, optional): Center of the phantom in mm. Default is (0,0).
- array (tuple, optional): Number of holes in x,y dimension. Default is (4,4).
- plot (bool, optional): Plot for debugging. Default is True.

Returns:

- pixel_size (tuple): Pixel size in both directions.
- number_of_resolved_line (tuple): Number of resolved lines in both directions.

10. threshold_determination

Description: Determine the threshold for signal present and signal absent
patches. Parameters:

- radius (float): Radius of disk in mm.
- noise_std (float): Standard deviation of noise.

- patch_size (int): Matrix size of the patch.
- fov (tuple): FOV of the original resolution phantom.
- matrix_size (tuple): Matrix size of the original resolution phantom.
- n_patch (int): Number of patches to generate for signal present or signal absent category.
- contrast (float): Contrast of the resolution phantom.
- plot (bool, optional): Plot for debugging. Default is False.

Returns:

- thre (float): Threshold for this disk radius, noise, patch size, contrast.
- acc_max (float): Maximum accuracy corresponding to this threshold.

11. low_contrast_detectability

Description: Low contrast detectability using the low contrast phantom.

Parameters:

- lc (ndarray): Low contrast phantom image.
- fov (tuple): Field of view in millimeters (mm).
- radius_range (tuple): (min_radius, max_radius) of disks.
- center (tuple): Center of the phantom.
- intensity (float, optional): Intensity of background. Default is 1.
- nspokes (int, optional): Number of spokes. Default is 10.
- spoke_dist (float, optional): Distance between disks within a spoke in millimeters (mm). Default is 20.
- disk_per_spoke (int, optional): Number of disks per spoke. Default is 3.
- plot (bool, optional): Plot the result. Default is True.
- contrast (float, optional): Contrast of the disks. Default is 0.3.
- noise_std (float, optional): Standard deviation of the additive Gaussian noise. Default is 0.0.

Returns:

- num_complete_spoke (int): Number of complete spokes, main metric.
- num_corr (ndarray): Number of correlated locations for each disk