Four-Dimensional Analytical Cardiac Magnetic Resonance Imaging Phantom in the Fourier Domain

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Introduction

A 2D analytical cardiac magnetic resonance imaging (MRI) phantom in the Fourier domain was introduced by Brummer et al. [1] to compare acceleration strategies based on a reduction of the field of view. In related work by our group and others the value of a standardized simulation phantom to test and compare reconstruction methods for cardiac imaging has become evident. In this work, a 4D analytical phantom in the Fourier domain is proposed, aimed to serve as a flexible, objective, standardized benchmark for evaluation and comparison of different image reconstruction techniques in dynamic 3D MRI.

Materials and Methods

The phantom design builds on the 2-D phantom, which introduced simulation of various types of motion that may be encountered in cardiovascular imaging. It extends the simulated object shapes to 3-D and adds additional anthropomorphic features, reflective of chest motion. The phantom was designed to reflect overall structure of the thorax, with features simulating different types of cardiac-synchronous motion. Dynamics are based on analytical harmonic functions with the periodicity of the heart beat, as well as some interpolated high-resolution real-life cardiac dynamic features. Data are generated in 4-D *k-t* space, using superimposed uniform cylindrical and ellipsoid object shapes. For generating *k*-space data of ellipsoid objects the mathematics presented by Koay et al. [2] were followed. Cylinders were generated using first order Bessel functions in radial dimensions, and a sinc function in the third dimension. The number of time samples and the spatial *k*-space grid size and shape are flexible. The phantom was programmed in MATLAB (The Mathworks Inc., Natick, MA, USA).

The following objects and motion dynamics were designed for the phantom, embedded in a dark (zero-valued) background:

1. A static double concentric cylindrical object simulating the chest wall.
2. A double concentric ellipsoid with contractile dynamics representing the left ventricle (1 in Fig. 1a). The dynamics of this object were derived from a short axis MRI scan of a normal subject, acquired at high temporal resolution (heart rate 60, true temporal resolution 14.3 ms, reconstructed at 160 phases).
3. A cylinder undergoing sinusoidal translational lateral motion in phase encoding direction (2, Fig. 1a).
4. A cylinder undergoing sinusoidal translational lateral motion in the readout direction (3, Fig. 1a).
5. A spherical object undergoing a sinusoidal intensity modulation cycle (4, Fig. 1a).
6. A cylindric object is subject to single-frame flash intensity changes (circle 5, Fig. 1a) which only differs from the background in one frame.
7. A large static oblate ellipsoid representing liver, located below the heart.
8. Two static vertical ellipsoids at the top of the phantom, simulating the lungs.

The *k*-space data may be generated on any type and size grid. The current implementation is sampled on a Cartesian 3-D grid, but extensions to generate radial and spiral sampling patterns are straightforward. By default the raw *k*-space data are written out to IEEE floating point standard complex-data file. A standard parameter structure is defined within the MATLAB code, which can also be written to a separate file to allow easy parameter transfer to any independent reconstruction program. The code includes provisions to add Gaussian random noise to the data at any desired level.

Results and Discussion

The phantom data set was generated on a 512×512×512 spatial sampling grid, with 160 temporal frames. An *x*-*y* plane cross-section after 3-D FFT reconstruction of the data (Figure 1a and 1b.z2) at z=0 shows the same objects and motion as the 2-D phantom of [1]. New content in other planes is illustrated in Figures 1b. Figure 1c shows a 3D rendering of the entire cardiac phantom at systole illustrating the content and the dynamics.

The current implementation does not yet include code for simulation of slice-selective excitation, for modulation of the image data by coil sensitivity maps, or for generating output grids other than cartesian. Future plans include the addition of these features, and public sharing of the phantom code. At present the MATLAB code, as well as the code for the original 2-D phantom, may be obtained from the authors upon request.

Conclusions

A 4D analytical cardiac MRI simulation phantom is presented with configurable data acquisition in the Fourier domain. It can be used as an objective and standardized benchmark to evaluate and compare sampling schemes and reconstruction methods. The phantom is well-suited for further feature enhancements such as incorporation of simulation of respiratory motion and modeling of T1 and/or T2 relaxation effects. The MATLAB code is available to other investigators.

References

1. Brummer ME et al. MRM 2004; 51(2):331–342
2. Koay CG Et al., MRM 2007; 58(2): 430-436

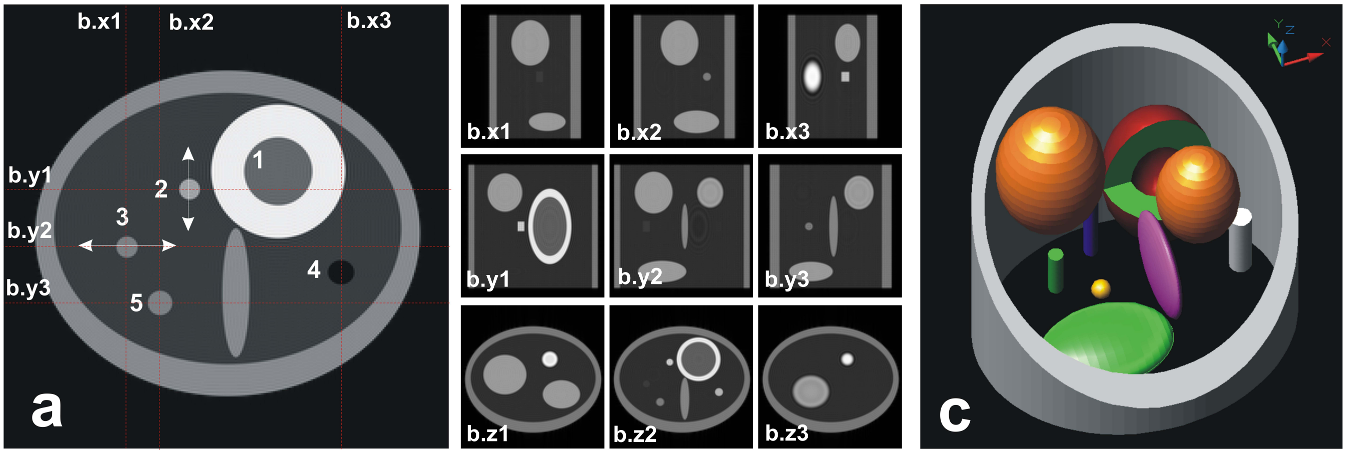

Figure 1. (a) An (axial) *x*-*y* plane cross-section through the phantom in "diastole". **(b)** Three slices through the 4D phantom in the *x*, *y* (locations shown in (a)) and *z* directions. Location *b.z2* (z=0) corresponds to (a) but shows systole. **(c)** A 3D rendering of the phantom, with portions removed to show the smaller objects.

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