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Processing Stack-of-Stars DCE Data

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ABSTRACT

Step-wise protocol for reconstruction of Stack-of-stars acquired DCE series, T1 and B1 maps and PK (pharmacokinetic) modeling of DCE data using a reference region model is provided.

Reconstruction of Stack-of Stars (SoS) radial k-space sampled DCE data

1 Image reconstruction

1.1 VFA and AFI images

The same reconstruction procedure is used for images acquired by the variable flip angle (VFA) and actual flip angle (AFI) stack-of-stars (SoS) pulse sequences.

1. Apply a Fourier transform in the slice direction to separate slices
2. Shift image in the slice direction to match geometry of reference T2-weighted image
3. Apply the following corrections to each view:
   3.1. Center each view in k-space by moving its peak to the center of k-space
   3.2. Phase normalize
   3.2. Correct for off-resonance frequency using the average phase difference between views in opposite directions
4. Re-grid radial k-space data to a 128x128 Cartesian grid as described by O'Sullivan et al. To summarize, for each slice:
   4.1. Multiply signal of each point by its respective area on a Voronoi diagram of the points (including zerofill points) in k-space
   4.2. Re-grid each radially defined point to its nearest Cartesian coordinates using its Kaiser-Bessel index
5. Apply Fourier transform to now Cartesian-defined k-space

CITATION

O'Sullivan, JD (1985). A Fast Sinc Function Gridding Algorithm for Fourier Inversion in Computer Tomography. IEEE Transactions on Medical Imaging.

LINK

10.1109/TMI.1985.4307723

1.2 DCE images

The k-space weighted image contrast (KWIC) method described by Song et al (2000 and 2004). was used to reconstruct the DCE images. To summarize, for DCE-MRI, the KWIC method uses radial acquisition's inherent oversampling of the k-space center by only using a subset of the acquired views in that region. By using a sliding window to select the views that are included in that central region, multiple images can be created from a single acquisition of k-space, thus increasing the temporal resolution.

After applying the KWIC, the resulting k-space data is reconstructed using the same method as **1.1- VFA and AFI Images**.

CITATION

Song HK, Dougherty L (2000). k-Space weighted image contrast (KWIC) for contrast manipulation in projection reconstruction MRI. Magnetic Resonance in Medicine.

LINK

https://doi.org/10.1002/1522-2594(200012)44:6<825::AID-MRM2>3.0.CO;2-D

CITATION

Song HK, Dougherty L (2004). Dynamic MRI with projection reconstruction and KWIC processing for simultaneous high spatial and temporal resolution. Magnetic Resonance in Medicine.
LINK
https://doi.org/10.1002/mrm.20237

2 B1 field map generation from AFI images

1. Compute pixel-wise actual flip angles using the equation

$$\alpha = \arccos \Big(\frac{rn - 1}{n - r} \Big) , \text{ where}$$

$$n = TR\_2/TR\_1 , \text{ and}$$

$$r = S\_1/S\_2 , \text{ where}$$

S_i is the signal intensity from the image acquired at TR_i .

2. Divide resulting actual flip angle maps by nominal flip angle to yield normalized pixel-wise B1 field maps.
3. Fit normalized B1 field maps to 3D 3rd degree polynomial using a least-squares fit to yield final B1 field maps used for T1 correction (step 3.1)

3 T1 map generation from VFA images

1. Compute T1 values using a non-linear least squares fit of the VFA image signal intensity to the Ernst equation

$$S(\alpha\_{act}) = M\_0 \Big(\frac{\sin\alpha\_{act} \ (1- E\_1)} {1- E\_1\cos \alpha\_{act}} \Big) , \text{ where}$$

$$E\_1 = e^{-TR/T\_1} , \text{ and}$$

$$\alpha\_{act} = B1*\alpha\_{nom} .$$

4 Generate tissue masks for reference region (muscle), kidney and tumor.

1. Open DCE images in an imaging processing software (eg. ImageJ)
   Note: Images immediately following contrast agent injection tend to outline structures well. Anticipating slight movement of the slices either due to respiratory motion or due to other reasons, a T2-weighted scan is usually acquired before the DCE sequence and used for ROI masking.

2. Create a mask accessible by your analysis software which defines skeletal muscle and any other ROIs of interest.

For example, on ImageJ:
1. Create a new empty image with same dimensions as DCE image in File -> New -> Image
2. Draw ROIs by hand and add to ROI Manager by pressing shortcut "t"
3. Set ROIs in empty image to a values for each tissue by Process -> Map -> Set
4. Save as raw image by File -> Save As -> Raw Data

5 DCE metric map generation from DCE images

5.1 Compute contrast agent concentration time-course from signal time-course for each voxel and for spinal muscle (reference region)

For each voxel:
1. Compute actual (B1-corrected) flip angle at voxel using \alpha = B1*\alpha_{nom}.
2. Normalize signal time course by mean signal prior to bolus injection

3. Compute T1 time-course using equation

$$T_1(t) = -TR \Big/ \ln\Big(\frac{A-S_R(t)} {A-S_R(t)\cos\alpha } \Big) , where$$

$$A = \frac{1 \ - \ e^{-TR/T_{1,0}}\cos\alpha}{1- e^{-TR/T_{1,0}}} and$$

T_{1,0} is the baseline T1, obtained from the previously generated T1 map (step 3)

4. Estimate contrast agent concentration time-course using equation

$$C(t) = \Big(\frac{1}{T_1(t)} - \frac{1}{T_{1,0}} \Big) \big/ R_{Gd} , where$$

$$R_{Gd} = 4.6 \textrm{/s}\cdot\textrm{mM}$$ (check for your specific contrast agent)

5.2 Compute spinal muscle (reference region) concentration time-course

1. Using a manually defined tissue mask for the spinal muscle, compute the mean concentration time-course for the entire muscle ROI

5.3 Compute quantitative DCE parametric maps

For each voxel:
1. Using the reference region model (Jones et al.) and the muscle as a reference tissue, fit for K^{trans} and v_e using the following equation:

\frac{dC_t}{dt} = \frac{K^{trans}_t}{K^{trans}_m}\frac{dC_m}{dt} \ + \ \frac{K^{trans}_t}{v_{e,m}}C_m \ - \frac{K^{trans}_t}{v_{e,t}}C_t, where

the reference K^{trans} of muscle, K^{trans}_m = 0.1/\textrm{min} ,
the reference v_e of muscle, v_{e,m} = 0.1 , and
C is the concentration of contrast agent, and the subscripts m and t refer to muscle (the reference region) and the tissue in the voxel being analyzed.

Note: K^{trans}_m and v_{e,m} are reference values, therefore voxel K^{trans} and v_e values are relative to those assigned when fitting for the equation above. The values of 0.1/\textrm{min} and 0.1 are from Cardenaz-Rodriguez et al.

CITATION

Jones KM, Pagel MD, Cárdenas-Rodríguez J (2018). Linearization improves the repeatability of quantitative dynamic contrast-enhanced MRI.. Magnetic resonance imaging.
LINK
https://doi.org/10.1016/j.mri.2017.11.002

CITATION

Cardenas-Rodriguez J, Howison CM, Pagel MD (2013). A linear algorithm of the reference region model for DCE-MRI is robust and relaxes requirements for temporal resolution. Magnetic Resonance Imaging.
LINK
https://doi.org/10.1016/j.mri.2012.10.008

6 Obtaining ROI metrics from maps

While pixel-wise parametric maps allow us to assess heterogeneity of a specific metric within the tumor, we also compute all parameters (K^{trans}, v_e) from the ROI of interest (tumor, kidney, and phantom):

1. Extract K^{trans} and v_e values for each voxel in the ROI.
2. Compute ROI metrics of choice (eg. mean, median, percentile values, standard deviation)

Note: To mitigate the impact of pixels whose K^{trans} and v_e values are outliers, we prefer median instead of mean of all pixels in the ROI.