Nonrigid 3D+t Image Registration for Temporal Averaging in Multiphase Coronary MR Angiography

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Target Audience: MR physicists and engineers interested in cardiac imaging, coronary angiography, and motion correction.

Purpose: High-resolution coronary magnetic resonance angiography (CMRA) enables finer depiction of coronary vessel detail, but at the same time introduces the challenge of compensating for a loss in SNR. Temporal averaging in a multiphase acquisition can improve the SNR, but requires a method to correct for interphase cardiac motion to avoid blurring. In this work, we demonstrate the ability of nonrigid image registration to estimate this motion and align multiple phase images so that temporal averaging can be performed. Importantly, we perform 3D+t image registration[1], which has two major advantages over standard 3D registration in this application. First, transformations are constrained to be temporally smooth in addition to spatially smooth, which is desirable for modeling cardiac motion. Second, registration is performed on all images simultaneously, relative to an implicit "mean" reference frame, so that results are not biased towards a specifically chosen reference image.

Methods: A free-breathing, multiphase 3D cones acquisition[2,3] was used to scan healthy volunteers and patients on a GE Excite 1.5 T scanner with an 8-channel cardiac coil. 3D translational motion correction was performed using 2D image-based navigators, and images were reconstructed with gridding. The spatial resolution was 0.8 mm isotropic, FOV was 28×28×14 cm^3, and three phase images were acquired per scan at a temporal resolution of 65 ms. 3D+t registration parameterized by B-splines[1,4] was used to estimate interphase motion. In this model, the multiple phase images were represented by a single 4D image $I(\boldsymbol{x},t)$, where $(\boldsymbol{x},t) \in \mathbb{R}^3 \times \mathbb{R}$, and the transformations at each point $\boldsymbol{T}_{\boldsymbol{\mu}}(\boldsymbol{x},t)$ were determined by minimizing a global intensity-based cost function:

$$C(\mu) = \frac{1}{|S||T|}\sum_{x\in S}\sum_{t\in T}\left(I(\boldsymbol{T}_{\boldsymbol{\mu}}(\boldsymbol{x},t)) - \bar{I}_{\mu}(\boldsymbol{x})\right)^2$$

μ are the B-spline parameters, S and T are the set of spatial and temporal coordinates, and $\bar{I}_{\mu}(\boldsymbol{x}) = \frac{1}{|T|}\sum_{t\in T} I(\boldsymbol{T}_{\boldsymbol{\mu}}(\boldsymbol{x},t))$ is the mean image over time after applying $\boldsymbol{T}_{\boldsymbol{\mu}}$. Because this is an underconstrained problem, the average deformation over time was additionally constrained to be the identity transform. $\bar{I}_{\mu}(\boldsymbol{x})$ thus represents a mean image that lies in the center of the dynamics described by the images, and intuitively each 3D phase image is registered to this implicit reference frame. Adaptive stochastic gradient descent was used to solve the optimization problem, and the highest resolution grid spacing for B-spline control points was 32×32×32 mm^3 in the spatial dimensions. After completing the registration, the original complex data from each coil was transformed and averaged, then re-combined. The averaging of three phases enabled an SNR gain of 1.7x.

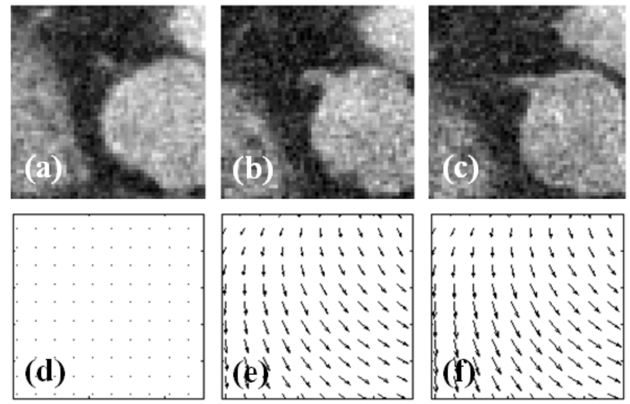

Figure 1. Original phase images and corresponding motion fields computed by 3D+t registration, for an axial slice through the RCA of a patient scan where vessel motion is in-plane. **(a,d)** depicts phase 1, **(b,e)** phase 2, and **(c,f)** phase 3. Motion fields are relative to phase 1 and scaled for ease of visualization.

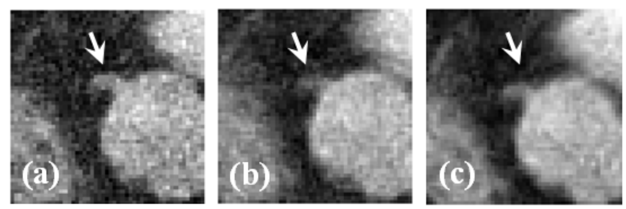

Figure 2. The same slice through the RCA of Fig. 1, in **(a)** the best phase image, **(b)** a temporally averaged image without 3D+t registration, and **(c)** a temporally averaged average with 3D+t registration. Arrows indicate a region where 3D+t registration improves vessel sharpness while retaining SNR gain. Some blurring still remains compared to the best phase image.

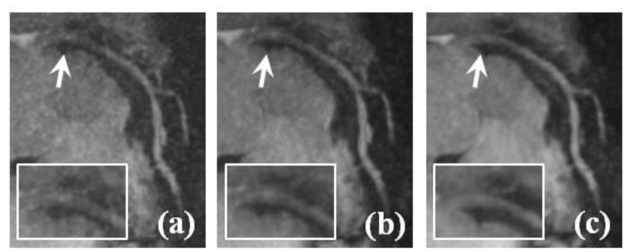

Figure 3. Patient scan depicting the LAD in **(a)** the best phase image, **(b)** a temporally averaged image without 3D+t registration, and **(c)** a temporally averaged image with 3D+t registration. Arrows indicate a region of increased vessel sharpness using 3D+t registration. View angle differs slightly between images since registration is performed in an implicit "mean" reference frame, and the optimal view for each image is shown.

Results and Discussion: Improved vessel sharpness was observed in areas of interphase motion when 3D+t registration was performed before temporal averaging, compared to when temporal averaging alone was performed. Fig. 1(a-c) shows the original phase images of an axial slice through a short segment of a right coronary artery (RCA), where the vessel motion is in-plane and easily visualized. The corresponding motion fields computed by 3D+t registration are plotted in Fig. 1(d-f), and are consistent with intuition. Fig. 2 shows that averaging the original phase images of Fig. 1(a-c) leads to an improvement in SNR compared with the best phase image, but suffers from significant motion blurring that is improved when 3D+t registration is used. Fig. 3 depicts the left anterior descending (LAD) artery from a patient scan. Again the temporally averaged image with 3D+t registration demonstrates improved vessel sharpness compared with the temporally averaged image without 3D+t registration, while retaining the SNR gain.

Conclusion: In this work, we have demonstrated the ability of 3D+t registration to correct for interphase cardiac motion, and consequently enable SNR improvement through temporal averaging of multiple phase images. The method may be adapted to other applications where interphase motion is an issue. Further work includes incorporating a mutual-information based metric that is more robust to intensity variance, and developing a metric to quantify registration performance.

References: [1] Metz CT, et al., Med. Image Analysis 15(2):238-249, 2011. [2] Wu H, et al., MRM 69(4):1083-1093, 2013. [3] Addy N, et al., Proc. 25th Intl Workshop on MRA: 84, 2013. [4] Klein S, et al., IEEE TMI 29(1):196-205, 2010.