Artifact-Free, Maximal-SNR, Efficient Image Combination for Coronary MR Using the Correlation Coefficient Template Grid Matching Technique

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Introduction: High quality coronary MR images must possess high SNR and minimal artifact. Conventional techniques, which acquire data over a period of many seconds, achieve high SNR but suffer from significant artifact due to coronary motion – even with compensation. An alternate approach is to use real-time MR. With real-time techniques, motion artifacts are inherently reduced since images are acquired rapidly compared to coronary motion. However, real-time images possess poorer SNR and resolution. To increase the SNR, a method has been developed recently for combining real-time coronary images[1]. Ideally, the combined image will possess both high-SNR as well as the minimal-artifact characteristics of it´s components. In practice, this will be achieved only if the combination procedure itself does not introduce artifact. In this study, the correlation coefficient (CC) template matching technique[2] will be presented for combining images in an efficient, SNR-optimal, and artifact-free manner.

Theory: A composite image is generated by adding n images $f_i(x,y)$; $i=1\cdots n$, together. If all images are equal to some initial template image $f(x,y)$ (apart from possible gain factors a_i due to increased blood flow and/or contrast agent), the composite image and SNR will be given by:

$$f_{comp}(x,y) = \Sigma(a_i c_i) f(x,y) \qquad (1)$$

$$SNR_{comp} = (f(x,y)/\sigma_n)[\Sigma(a_i c_i)/(\Sigma c_j^2)^{1/2}] \qquad (2)$$

where the c_i´s are arbitrary weighting coefficients, and σ_n is the noise in $f(x,y)$. The CC technique combines images from a real-time series without introducing artifact by identifying the subset of images that are identical to the template. This is accomplished by calculating the CC between the template and every location in every image of the real-time series. The maximum value of the CC (=CC_{max}) in each image determines how closely the image resembles the template. It can be shown that an image and template are identical within noise with a u% confidence level if:

$$CC_{max} \geq \tanh\{\tanh^{-1}\{<CC_{max}>\}+\mu_{CC} + \sigma_{CC} Z_u\} \qquad (3)$$

where: $<CC_{max}> = 1-(\sigma_n/\sigma_f)^2$, $\mu_{CC} = <CC_{max}>/[2(N \cdot M -1)]$, $\sigma_{CC} = 1/(N \cdot M-3)^{1/2}$, Z_u is the Gaussian Z-score corresponding to a u% confidence level, σ_f is the standard deviation of the pixels in the template, and N, M are the x and y template dimensions.

Selecting a subset based on Eq. 3 will ensure that all $f_i(x,y)$, and thus $f_{comp}(x,y)$, will be identical to the template within noise. However, Eq. 2 implies that the noise will depend on the choice of c_i´s. The performance of the image combination technique with different c_i´s can be assessed by the similarity between the template and f_{comp}. This can be determined by evaluating CC_{max} between the two (=CC_{comp}). It can be shown that the expected value of CC_{comp} is given by:

$$<CC_{comp}> = <CC_{max}>/\{1-(\sigma_n/\sigma_f)^2[1-(1/SNR_{comp})^2]\}^{1/2} \qquad (4)$$

Using the method of Lagrange multipliers, $<CC_{comp}>$ and SNR_{comp} can be maximized simultaneously by setting: $c_i=a_i$; $i=1\cdots n$. By combining images in this manner, artifact-free composite images can be generated with maximal SNR, and maximal similarity.

One potential difficulty with the above technique is efficiency. Since coronary motion is non-rigid body and through-plane, only a small fraction of images will likely be identical to within noise. A possible method to improve the efficiency is to use smaller templates. Over the reduced portion of the anatomy covered by smaller templates, rigid-body motion is more likely. However, a smaller template may not cover the entire artery. Artifact may then be introduced in regions of the artery that lie outside of the template. To remedy this situation, a grid of small templates can be used (Fig. 1a). The CC_{max} values of each template grid element can be assessed independently for each image. Different portions of different images can then be combined. With this approach, the fraction of usable images can be increased, without reducing the extent of the anatomical coverage of the template.

Methods: A 60 second series of 3-interleaf spiral images was acquired of the left coronary artery (LCA). Images were acquired at a spatial resolution of 2.2mm at an interpolated frame rate of 24 frames/s. A 3x2 grid of 16x16 pixel templates covering the LCA was generated (Fig. 1a). Image combination was performed using one to thrity images from the subset of images satisfying Eq. 3 with an 84% confidence level. Measured CC_{comp} values were compared to Eq. 4. For further analysis, an edge-detection algorithm[4] (Fig. 2f) was used to compare the vessel edge position in $f_{comp}(x,y)$ and the template.

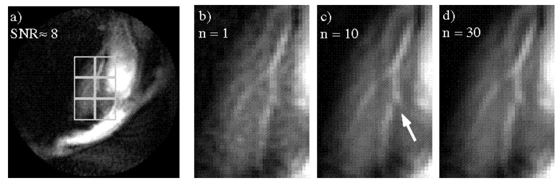

Figure 1: *(a) Initial image containing a template grid. (b) Closeup of the template region. Composite images with n = (c) 10 and (d) 30.*

Results: Figure 1 demonstrates that the SNR is significantly improved in the composite images relative to the template. Qualitatively, the proximal portions of the arteries appear similar in both, while the distal portions, in particular a bifurcation point (arrow), are more easily discernable in the composite images. Figure 2a is a plot of CC_{comp} for one of the template grid elements. Results for the other elements are similar. CC_{comp} is slightly greater than predicted theoretically, due to approximations inherent in Eq. 4 as well as bias introduced due to the CC_{max} cutoff value set at only the 85\% confidence level. This is tolerable since a larger than expected CC_{comp} implies a greater similarity. CC_{comp} reaches a steady state when the similarity between f_{comp} and the template becomes limited by the noise in the template. This point is illustrated by the fact that little additional structure is observed in going from 10 to 30 component images in Figs. 1c,d. Figure 2b indicates that SNR_{comp} increases roughly as $\sqrt{n}$. Although images were combined with $c_i=a_i$, this is the same result that is expected when all the c_i´s are equal. In fact, figure 2c indicates that there is little change in either SNR_{comp} or CC_{comp} when using optimized versus equal weighting coefficients for the combination. This is because, in this case, the range of a_i's is small (Fig. 2d). Fig. 2e indicates that the mean absolute discrepancy between the vessel edge position in the template and composite images is less than half a pixel. Since half pixel shifts due to partial volume effects are expected, the CC technique does not alter the location of the vessel edge.

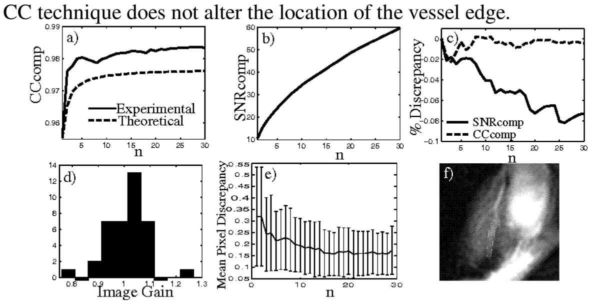

Figure 2: *(a) CC_{comp} vs. n. (b) SNR_{comp} vs. n. (c) Difference in results obtained using equalized and optimized c_i's. (d) Histogram of a_i´s. (e) Mean absolute discrepancy in vessel edge location between the template and f_{comp}. (f) Example of vessel tracking.*

Discussion: The results of this study indicate that the CC technique is capable of combining images without introducing artifact. By using a template grid, smaller templates could be used for greater efficiency without sacrificing anatomical coverage. There did not appear to be a significant advantage, either in terms of CC_{comp} or SNR_{comp}, to weighting images in an optimal manner. This was because the intensity of the component images was relatively uniform. This may not be the case if contrast agent is used or if coronary flow is unstable due to disease.

[1] Hardy, C.J., *et al., Proc. 6th ISMRM*, 22, 1998,[2] Sussman, M.S. *et al., Proc. 7th ISMRM*, 2002, 1999,[3] Sussman, M.S. et al., *Proc. 8th ISMRM*, 1703, 2000,[4] Robert, N. *et al., Med. Phys.,*, **21**, 1360, 1994

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