Validation of Nonrigid Registration for Cardiac Cine MR Time Series

G. Li[1], L. Zhang[1], C. Guetter[1], and C. Chefd'hotel[1]
[1]Siemens Corporate Research, Princeton, New Jersey, United States

Problem: Validation of cardiac image registration has been a challenging task due to the lack of ground truth and severe through-plane motion. Since a consistent and transitive registration algorithm is more likely to find a biologically meaningful mapping between corresponding points when the topology is preserved [1], in this work we focused on quantitatively evaluating the registration consistency, transitivity, and the consistency sensitivity to cardiac motion as the indicators of registration performance.

Methods: To evaluate the registration consistency [2], we propose a volume consistency registration error $VCRE = \log|D(\psi_{TS} \circ \phi_{ST})| + \log|D\phi_{ST}|$, which is derived from the conventional consistency registration error $CRE = \|\psi_{TS} \circ \phi_{ST} - id\|$, where ϕ_{ST} and ψ_{TS} denote the transformations that align the source (S) to target (T) image and T to S, *id* is the original position of points on the image domain before deformation, $|D\phi|$ the Jacobian map of ϕ and $\|\cdots\|$ the standard Euclidean norm. The VCRE is more reliable than the CRE, since Jacobian map based consistency measure provides information on local contraction and expansion and is more reliable for consistency analysis, which was experimentally proved. The VCRE should be close to 0, if the registration algorithm is consistent. The transitivity of a registration algorithm is evaluated by the transitivity registration error $TrRE = \|\phi_{CA} \circ \phi_{BC} \circ \phi_{AB} - id\|$. To assess the consistency sensitivity to cardiac motion, a Fourier transform is applied to all ε_{VCRE} in a time series: $\varepsilon_{VCRE} \rightarrow E_{VCRE}(2\pi f)$, where ε denotes a statistical operator (e.g. mean, root mean square), *n* is the index of the image pair and *f* the frequency in Hz. If a nonrigid registration algorithm is sensitive to cardiac motion, then E_{VCRE} should reveal a peak around the heart rate; otherwise the spectrum of E_{VCRE} should be evenly distributed. In the end, the accuracy was calculated as the root mean square (RMS) of point-to-contour distance [4] for the points on two contours that were outlined by physicians, indicating endocardium and epicardium on the frames corresponding to the phase of diastole and systole of a cardiac cycle. Using these criteria, a diffeomorphic nonrigid registration (D-NRR) [5] was compared with its symmetric version (SD-NRR) [4] using 10 cardiac cine MR time series (SSFP, 1.5T) acquired from 10 volunteers. Each cine time series consists of two long axis and 10-12 short axis with slice thickness 6 or 8mm; 14-20 images of different time phases were acquired at each slice location with pixel spacing 1.33-1.56mm. Since the apex and base regions are suffering from the severe through-plane motion, six slice locations in the middle areas were selected to calculate the mean and standard deviation of VCRE and TrRE. Furthermore, four images representing diastole, systole and their middle phases of every slice location were selected as the target image to investigate the effect of target image on consistency error.

Results: Using the validation criteria, we were able to quantify the performance of the registration algorithms. SD-NRR, with mean VCRE and TrRE equal to -0.0028 ± 0.0173 and 0.1979 ± 0.2642 pixel is more volume consistent and transitive than D-NRR, with mean VCRE and TrRE equal to -0.0075 ± 0.0476 and 0.3733 ± 0.2642 pixel. The VCRE and TrRE in the area closer to the base are larger than those closer to the apex, since the areas suffering from the severe through-plane motion are larger. Additionally, choosing the diastole or systole phase as the target image will result in a larger consistency error due to the large magnitude of cardiac motion. Fig. 1 exemplarily shows RMS of VCRE (left) and TrRE (right) of the two nonrigid registration methods for data 1 (2 long axis, 10 short axis, 20 time phases), exhibiting that the middle area has a smaller VCRE and TrRE than the base area. The consistency sensitivity to cardiac motion was revealed by the frequency domain analysis: the VCRE of D-NRR was more dependent on motion than SD-NRR, as evidenced by higher frequency amplitudes and more significant peaks around the heart rates. The resulting average heart rate of 10 time series is all in the range of normal heart rate for a healthy adult: 60 to 100 beats per minute (BMP). Fig. 2 shows an example of frequency domain analysis using the slice location close to the base area of data 1, revealing that the consistency of D-NRR is more dependent on cardiac motion and its frequency peak is approximately equal to 75 BMP. The results of accuracy present that both nonrigid registration algorithms have the same accuracy level: average accuracy of D-NRR and SD-NRR are 1.5325 ± 0.9796 pixel and 1.7311 ± 0.9957 pixel.

Conclusion: Besides visual inspection and calculating the accuracy of nonrigid registration algorithms on cardiac cine time series, we are able to determine the consistency, transitivity, consistency sensitivity to cardiac motion of those algorithms, giving a more comprehensive picture of the registration performance on cardiac data sets.

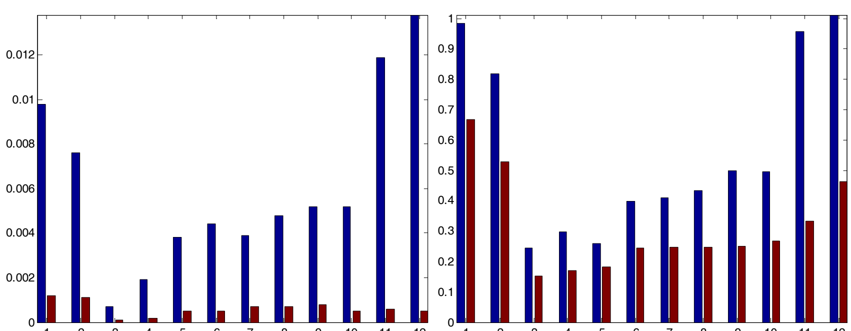

Fig. 1: Bar charts of rms VCRE (left) and rms TrRE (right) of the two nonrigid registration algorithms (blue: D-NRR, red: SD-NRR) for data 1; 1, 2: long axis; 3-12: short axis, from apex to base

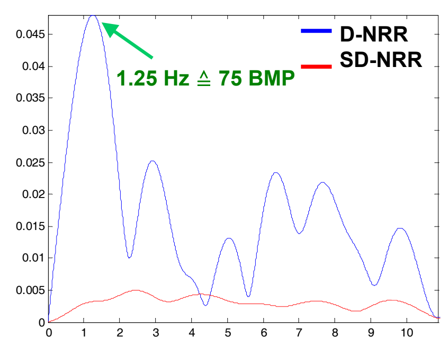

Fig. 2: An example of frequency domain analysis, showing the consistency of D-NRR is more sensitive to cardiac motion.

References [1] G.E. Christensen et al., *IEEE Trans. Med. Imaging* 20:568-582 (2001) [2] C. Tanner et al., *MICCAI* 2488:307-314 (2002) [3] G.E. Christensen *et al., J ELECTRON IMAGING* 12:106-117 (2003) [4] M.P. Jolly et al., *ISBI* 484-487 (2010) [5] C. Chefd'hotel et at., *ISBI* 753-756 (2002)