Towards CT Enhanced Ultrasound Guidance for Off-pump Beating Heart Mitral Valve Repair

Feng P. Li[1,2], Martin Rajchl[1,2], James A. White[1,3], Aashish Goela[4], and Terry M. Peters[1,2]

[1] Imaging Research Laboratories, Robarts Research Institute, London, ON
[2] Biomedical Engineering Graduate Program, Western University, London, ON
[3] Division of Cardiology, Department of Medicine, Western University, London, ON
[4] Department of Medical Imaging, Western University, London, ON

Abstract. Off-pump beating heart interventions require a good guidance system to show both cardiac anatomy and motion. Over the years, echocardiography has become a popular solution for such a purpose because of its real-time imaging capability, flexibility, non-invasiveness, and low cost. However, it can be difficult for surgeons to appreciate the position and orientation of 2D images and to keep surgical tools and targets both shown in the image plane with only ultrasound guidance. In this paper, we propose to use CT images as high-quality 3D context to enhance ultrasound images through image registration to provide a better guidance system with very few changes to standard workflow. We have also developed a method to generate synthetic 4D CT images through non-rigid registration, when dynamic pre-operative CT images are not available. The validation of synthetic CT images was performed by comparing them to real dynamic CT images and the validation of CT-ultrasound registration was performed with static, dynamic, and synthetic CT images.

Keywords: image-guidance, beating-heart interventions, synthetic CT, CT-enhanced ultrasound guidance.

1 Introduction

Mitral valve prolapse (MVP) is a common valvular abnormality that can cause severe non-ischaemic mitral regurgitation[3]. The cause of MVP can be histological abnormalities of valvular tissue, geometric disparities between the left ventricle and mitral valve (MV), or various connective tissue disorders[4]. Implantation of artificial chordae tendineae is a widely used technique for correction of both posterior and anterior leaflet prolapse[2]. The conventional surgical approach for mitral valve repair usually requires a full or partial sternotomy and the use of a heart-lung machine, also referred as the "pump". Recent developments in cardiac surgery, however, have made it possible to perform the repair in a minimally-invasive manner on a beating heart ("off-pump")[1]. However, these

C.A. Linte et al. (Eds.): MIAR/AE-CAI 2013, LNCS 8090, pp. 136–143, 2013.

minimally invasive approaches are often limited by the lack of a direct view of surgical targets and/or tools, a challenge that is compounded by potential movement of the target during the cardiac cycle. For this reason, sophisticated image-guided navigation systems are required to assist in procedural efficiency and therapeutic success.

Guidance systems for off-pump beating heart interventions must show both cardiac anatomy and tissue motion. Echocardiography (ultrasound), because of its real-time imaging capability, flexibility, non-invasiveness, and low cost, is frequently employed in cardiac surgery as both a monitoring and imaging modality. However, safety concerns exist since it can be difficult for surgeons to appreciate the position and orientation of 2D images relative to a surgical tool, and to keep the tool tip and target in the image plane simultaneously. As alternatives, fluoroscopy can only provide real-time 2D projection images , while poorly demonstrating the target anatomical structures; intra-operative MRI has the capability of displaying cardiac anatomy and motion dynamically during interventions[7], but is very expensive, requires developments of novel, non-ferromagnetic tools and devices, and is unavailable in most institutions. To overcome these limitations, Moore et al.[9] described a navigation system for off-pump beating heart mitral valve repair, in which the bi-plane transesophageal echocardiogram (TEE) images were augmented by a virtual presentation of selected anatomical models, i.e. mitral valve annulus (MVA) and aortic valve annulus (AVA), which were defined by manually identified feature points on the TEE images right before the surgery started. Animal studies showed that the augmented virtuality guidance that they employed significantly improved the efficiency, accuracy, and safety of the procedure that involved guiding the surgical tool from the entry point at the cardiac apex to the target area, compared to TEE-only guidance. However, the virtual anatomical model were not dynamically updated and could be centimeters away from the actual position due to physical movement of the target during the surgery.

In this paper, we propose a guidance system that improves on Moore's work by employing CT-enhanced ultrasound images for guiding such procedures. Both CT and ultrasound are commonly used in the standard clinical workflow for cardiac interventions, so the proposed approach requires very few changes in the image acquisition workflow. In this guidance system, intra-operative TEE images display the real-time cardiac anatomy and motion, while the pre-operatively acquired high spatial resolution CT images are dynamically fused with the TEE images to provide a high quality 4D context. We also developed a method to generate patient-specific synthetic 4D CT image sequences based on a static CT image and 4D ultrasound images to avoid the need to acquire high-dose retrospectively-gated CT scans[5]. We validated and compared the accuracy and efficiency of different registration approaches with both real and synthetic CT images, with respect to the mitral valve annulus, the target for procedures that aim to repair the mitral valve.

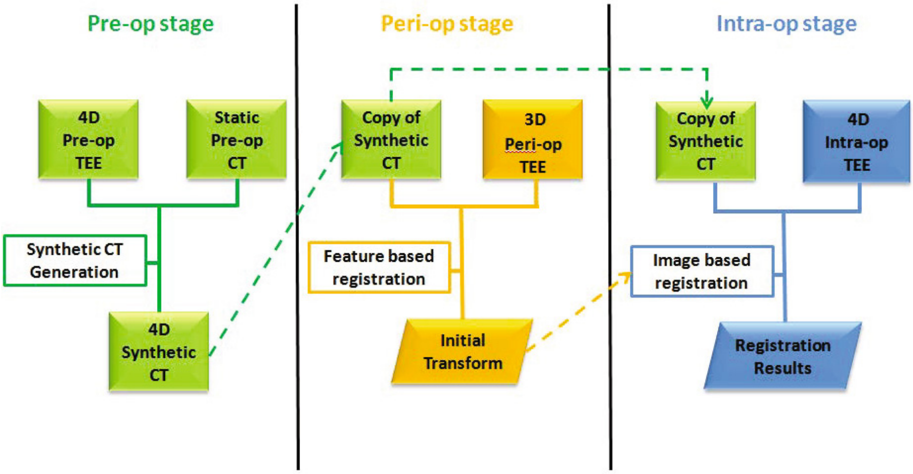

Fig. 1. The suggested clinical workflow of how to use CT-enhanced ultrasound guidance for off-pump beating heart interventions

2 Methods

2.1 Suggested Clinical Workflow

The suggested clinical workflow for using CT-enhanced ultrasound guidance is illustrated below (Fig. 1). In the pre-operative stage, 4D CT images are either acquired by performing a retrospectively gated CT scan or generated based on a static CT and 4D ultrasound images from the same patient using the proposed synthetic CT generation method. The 4D CT images are transferred to the guidance system and brought to the operation room prior to surgery.

In the peri-operative stage, an initial registration is performed between a peri-operatively required 3D ultrasound volume and a CT image at the same or closest cardiac phase using feature based registration. Features, such as the inner walls of the left ventricles, are semi-automatically segmented using an approach described in [11]. The resulting registration transform is then saved and used as an initialization for the intra-operative CT to ultrasound registration.

In the intra-operative stage, CT images are registered to the intra-operatively acquired TEE images using rapid GPU-based algorithm. The registered images can be visualized in different formats according to surgeon's preference, such as directly overlaying TEE images onto CT, displaying the volume rendering CT images within the visualization environment, or simply extracting critical features from these images and displaying them fused the CT or TEE volumes. In this way, visual linkage can be provided between the intra-operative images, pre-operative image, anatomical models, and surgical tools within the same guidance framework.

2.2 Generation of 4D Synthetic CT

The generation of the synthetic dynamic CT images is performed through non-rigid registrations between ultrasound images [12] over a single cardiac cycle to obtain patient specific heart motion maps, in the form of deformation fields, and to apply these vector maps to CT images to provide synthetic animation. In this approach, at least one sequence of 3D TEE images, representing at least one complete cardiac cycle, and one single frame cardiac CT images must be acquired pre-operatively.

The procedure begins with the selection of a single 3D TEE image, acquired at a cardiac phase close to the static CT image as a reference and rigidly registering it to the static CT image. The rigid registration is performed by semi-automatically segmenting the inner wall of the left ventricles from both the reference TEE image and the static CT image, aligning the segmented ventricles with the Iterative Closest Point (ICP) method, and refining the alignment with a mutual information based registration [6] . All the other TEE images in the 4D sequence are then rigidly registered to the reference image as initialization for the later non-rigid transform.

After the initial rigid registration step, non-rigid registrations are performed amongst the ultrasound images in the 4D sequence. To obtain the deformations fields that relate the reference image to all the other images in the sequence, we can either perform registration directly between the reference image and each member of the sequece, between temporally adjacent images, or in a group-wise manner [13]. The deformation fields are then employed as cardiac motion maps and applied to the static CT image to generate a synthetic dynamic CT sequence. By performing this approach for each frame, we can generate an entire sequence of synthetic dynamic CT images with the same temporal resolution as the 4D TEE images. The non-rigid registration method we employed is the mult-resolution fast free-from (F3D) deformation registration method described by Modat et al. [8], because of its capability of handling the morphological deformation due to cardiac motion and providing relatively smooth deformation fields.

2.3 GPU-Based Real-Time Registration

During the intra-operative stage, real-time image registration is performed between intra-operative and pre-operative images. Dynamic CT images obtained from retrospectively gated scans, synthetic CT images generated by our method, and pre-operative 4D TEE images, can potentially fulfill the role of pre-operative images in the proposed system. CT images can be registered to the intra-operative TEE images in two different ways. The first is to perform online registration directly between the CT images and intra-operative TEE images, using a multi-modality registration method. The second is to perform the registration between CT images and pre-operative TEE images prior to the surgery, perform online registration between intra-operative and pre-operative TEE images during the surgery, and then combine the two transforms to achieve registration between CT and intra-operative TEE images. The potential benefit of the second method is that the off-line registration can be verified by clinicians prior to the procedure to ensure optimized results, and the online registration is between images of a single modality (i.e. ultrasound), which can potentially be performed more efficiently and reliably. We used mutual information (MI) as the similarity metric for CT to TEE registration, while employing sum of squared differences (SSD) for TEE to TEE registration. Validation of these methods is presented below.

In this project we perform rigid registration between intra- and pre-operative images at corresponding cardiac phases. To accelerate this process, bringing it close to real-time, the registration algorithms are parallelized on graphic processing units (GPUs). The registration pipeline contains three components: image transform, linear interpolation, and similarity metric computation. In this case, image transform and interpolation can be completely parallelized and very efficiently implemented on a GPU, since the operation on each voxel is identical and independent. However, the similarity metric computation, either MI or SSD, cannot be perfectly parallelized due to potential race conditions [10], that is caused by access to a shared memory address by multiple processing threads without proper synchronization which can lead to unexpected results. We therefore use a recursive method, that divides the entire volume into small blocks first and then iteratively sums up the intermediate results, to achieve partial parallelization for this computation.

3 Experiments and Results

3.1 Validation of Synthetic CT

The validation of the quality of synthetic CT images is perform by comparing the synthetic images to real dynamic CT volumes. We performed the validation the data from five patient. For each patient we acquired a dynamic CT sequence representing one cardiac cycle and a 4D TEE sequece representing several cardiac cycles. The first images in the dynamic CT sequence was used as a static CT image from which synthetic CT images were generated. Then, we manually segmented the left ventricles from both dynamic and synthetic CT images and compared them at corresponding cardiac phases with respect to the Dice Similarity Coefficient(DSC) and root mean square errors (RMSe). The results are shown in Table 1.

Table 1 demonstrates that the left ventricles in the synthetic CT images were quite similar as the ones in the dynamic CT images with a mean DSC of 0.82 and mean RMS of 2.96mm. However, the comparison results at diastolic frames, such as frame 2 and 10, are better than the results at systole (frame 4 and 5). One possible reason for this phenomenon is that patients were under general anesthesia when taking TEE scans, while they were awake when taking dynamic CT scans.

Table 1. Comparison of left ventricles between synthetic and dynamic CT images over one cardiac cycle of five patients

# of frame	2	3	4	5	6	7	8	9	10
DSC(mean)	0.86	0.81	0.77	0.77	0.80	0.83	0.83	0.85	0.87
DSC(σ)	0.03	0.02	0.05	0.05	0.03	0.04	0.05	0.04	0.03
RMS(mean)	2.48	3.11	3.67	3.63	3.28	2.74	2.71	2.59	2.42
RMS(σ)	0.60	0.46	0.88	0.58	0.77	0.84	0.43	0.21	0.27

*RMS measurements in mm

3.2 Validation of CT-TEE Registration

In order to examine the impact of introduing dynamic and synthetic CT images to the guidance system, we performed CT-TEE registration using static, dynamic, and synthetic CT images. The static CT images used in this experiment were acquired at end-diastole. We manually segmented the mitral valve annulus (MVA), which indicates the target area in the mitral valve repair procedure, and used it for the target registration error (TRE) tests. Two registration approaches were used. The first directly performs multi-modality registration between pre-operative CT and intra-operative TEE images, while the second separates the registration into two stages, CT-TEE registration at pre-operative stage and TEE-TEE registration at intra-operative stage. The first approach uses mutual information as a similarity metric, while the second uses SSD. The validation was performed on five patients' data and for each patient we used image sequences representing two cardiac cycles. The result is shown in Table 2.

Table 2. Comparison of TRE w.r.t. MVA with static, dynamic, and synthetic CT images (mm)

CT-TEE Registration

CT type	Static		Dynamic		Synthetic	
Cardiac phase of TEE	ES	ED	ES	ED	ES	ED
RMS (mean)	9.00	4.90	3.94	4.94	4.59	4.12
RMS (σ)	2.51	0.95	1.37	0.74	1.22	0.41

CT-TEE + TEE-TEE Registration

CT type	Static		Dynamic		Synthetic	
Cardiac phase of TEE	ES	ED	ES	ED	ES	ED
RMS (mean)	10.37	5.56	4.59	5.23	5.91	4.29
RMS (σ)	1.36	2.25	0.33	1.52	2.08	1.03

*ES: end-systole, ED:end-diastole

Table 2 shows that, with both registration approaches, using only a static CT image for registration can result in large TRE errors when the TEE image was acquired at a different cardiac phase. However, this error can be reduced by using dynamic or synthetic CT images. The result showed that using the synthetic CT images generated by our method led to results similar to those obtained from

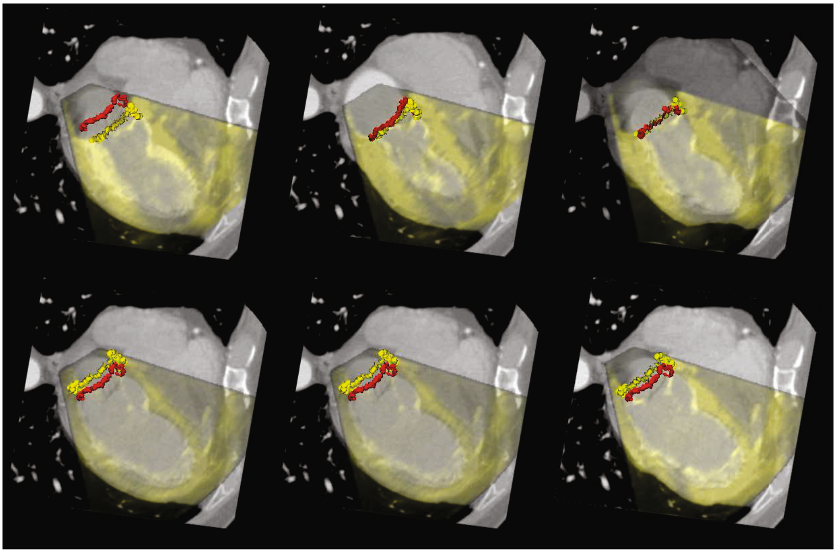

Fig. 2. An example of registration results. First row: results at end systole; Second row: results at end diastole; Left column: registration using static CT; Middle column: registration using dynamic CT; Right column: registration using synthetic CT. TEE images are shown in yellow, while CT images are shown in grey. The yellow curves represent MVA from TEE, while the red curves represent MVA from CT.

actual dynamic CT images. However, using synthetic CT can greatly reduce the radiation dose applied to patients.

Comparing the two registration approaches, it can be observed that the result of directly CT-TEE approach was slightly better than the two-stage approach. A possible reason for this is that the two-stage method introduced registration errors in both of the stages and these errors were accumulated. However, the two-stage approach showed better efficiency at the intra-operative stage, requiring 227±63ms to perform a TEE-TEE registration using SSD, while the direct approach required 430±182ms to perform a CT-TEE registration using mutual information.

4 Discussion and Conclusion

We proposed a CT-enhanced ultrasound guidance system in which pre-operative CT images and intra-operative TEE images are fused to provide both real-time cardiac motion and high quality 3D anatomy context. The proposed solution can provide a linkage between pre-operative and intra-opertive images and flexibility in visualization formats. It is cost-effective and requires very few changes to the current standard workflow. We have also developed a method to generate synthetic 4D CT images to be used in the guidance system. The validation showed that by introducing synthetic CT images to the system, we can achieve better results than using a static CT image and similar results to the use of actual dynamic images, without applying high radiation dose to the patient.

References

[1] Bajona, P., Katz, W.E., Daly, R.C., Zehr, K.J., Speziali, G.: Beating-heart, off-pump mitral valve repair by implantation of artificial chordae tendineae: an acute in vivo animal study. The Journal of Thoracic and Cardiovascular Surgery 137(1), 188–193 (2009)

[2] David, T.E., Ivanov, J., Armstrong, S., Christie, D., Rakowski, H.: A comparison of outcomes of mitral valve repair for degenerative disease with posterior, anterior, and bileaflet prolapse. The Journal of Thoracic and Cardiovascular Surgery 130(5), 1242–1249 (2005)

[3] Freed, L., Levy, D., Levine, R., Larson, M., Evans, J., Fuller, D., Lehman, B., Benjamin, E.: Prevelence and Clinical Outcome of Mitral Valve Porlapse. The New England Journal of Medicine 341(1), 1–7 (1999)

[4] Hayek, E., Gring, C.N., Griffin, B.P.: Mitral valve prolapse. Lancet 365(9458), 507–518 (2005)

[5] Hirai, N., Horiguchi, J., Fujioka, C., Kiguchi, M., Yamamoto, H., Matsuura, N., Kitagawa, T., Teragawa, H., Kohno, N., Ito, K.: Prospective versus Retrospective ECG-gated 64-Detector Coronary CT Angiography: Assessment of Image Quality, Stenosis, and Radiation Dose. Radiology 248(2), 424–430 (2008)

[6] Maes, F., Collignon, A., Vandermeulen, D., Marchal, G., Suetens, P.: Multimodality image registration by maximization of mutual information. IEEE Transactions on Medical Imaging 16(2), 187–198 (1997)

[7] Mcveigh, E.R., Guttman, M.A., Kellman, P., Raval, A.N., Lederman, R.J., Cardiology Branch A N R.: Real-time, Interactive MRI for Cardiovascular Interventions. Acad. Radiol. 12(9), 1121–1127 (2005)

[8] Modat, M., Ridgway, G.R., Taylor, Z.A., Lehmann, M., Barnes, J., Hawkes, D.J., Fox, N.C., Ourselin, S.: Fast free-form deformation using graphics processing units. Computer Methods and Programs in Biomedicine 98(3), 278–284 (2010)

[9] Moore, J., Wedlake, C., Bainbridge, D., Guiraudon, G., Chu, M., Kiaii, B., Lang, P., Rajchl, M., Peters, T.: A navigation platform for guidance of beating heart transapical mitral valve repair. IEEE Transactions on Biomedical Engineering (2012)

[10] Netzer, R.H.B., Miller, B.P.: What Are Race Conditions? Some Issues and Formalization of Wisconsin. Journal ACM Letters on Programming Languages and Systems 1(1), 74–88 (1992)

[11] Rajchl, M., Yuan, J., White, J.A., Nambakhsh, C.M.S., Ukwatta, E., Li, F., Stirrat, J., Peters, T.M.: A fast convex optimization approach to segmenting 3D scar tissue from delayed-enhancement cardiac MR images. In: Ayache, N., Delingette, H., Golland, P., Mori, K. (eds.) MICCAI 2012, Part I. LNCS, vol. 7510, pp. 659–666. Springer, Heidelberg (2012)

[12] Wierzbicki, M., Drangova, M., Guiraudon, G., Peters, T.: Validation of dynamic heart models obtained using non-linear registration for virtual reality training, planning, and guidance of minimally invasive cardiac surgeries. Medical Image Analysis 8(3), 387–401 (2004)

[13] Wu, G., Yap, P.-T., Wang, Q., Shen, D.: Groupwise Registration from Exemplar to Group Mean: Extending Hammer to Groupwise Registration. In: Proceedings of the Conference on Information Processing in Medical Imaging, pp. 396–399 (2010)