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Estimating heart movement and morphological changes during robot-assisted coronary artery bypass graft interventions

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Keywords Robot-assisted coronary assisted bypass grafting · Pre-operative planning · Peri-operative workflow-induced heart displacement · Real-time trans-esophageal echocardiography · Magnetic surgical tracking technology.

Introduction

In robot-assisted coronary artery bypass graft (RA-CABG) procedures, a pre-operative computed tomography (CT) scan of the patient is used to assess patient candidacy prior to the intervention and also to identify the optimal port locations to ensure proper access to the target vessels with the robotic instruments [1]. In addition, often the target vessel cannot be easily identified intra-operatively and surgeons must predict where the same target would be located intra-operatively based on the pre-operative image.

However, the position and morphology of the heart may change during the various peri-operative work-flow stages (lung deflation, chest wall insufflation etc.) and consequently the surgical targets and features used to assist with the image-to-patient registration may also move. As such, before any pre-operative image data can be used intra-operatively to either identify optimal port locations or locate the surgical targets, they must be adequately updated to take into account any changes that occur during the procedure [2]. Therefore, measuring the extent of heart movement during the peri-operative workflow, as well as any morphological changes in the features of interest is critical for optimal procedure planning and intra-operative guidance to avoid conversions to an open chest procedure and maintain procedure efficacy.

Methodology

To measure the effects induced in the heart morphology during the peri-operative work-flow, we acquired "instances" of the heart of patients undergoing robot-assisted coronary artery bypass grafting using real-time 2D trans-esophageal echocardiography (TEE) at three stages during the procedure: Stage 1 – anesthetised and double lung ventilation; Stage 2 – single lung ventilation; and Sage 3 – 10 cm H_2O chest wall insufflation. The ultrasound images were acquired using a magnetically tracked Agilent Technologies Model 21369A trans-esophageal echocardiography (TEE) transducer (Agilent Technologies, Canada). The US probe was modified by embedding a 6 degree-of freedom NDI Aurora (Northern Digital Inc., Canada) magnetic sensor coil inside the casing of the transducer [3], and calibrated using a Z-string approach [4]. This technology enabling spatial tracking of the transducer and acquired image within the magnetic field centered around the heart and produced by a magnetic field generator located underneath the patient's thorax, under the operating table (Fig. 1).

Following Research Ethics Board approval and patient consent, two dimensional US images of four patients' hearts were acquired at mid-diastole after patient intubation (Stage 1), while the imaging fan was rotated in 20 degree increments. The acquisition was then repeated after single-lung deflation (Stage 2) and after 10 cm H_2O chest wall insufflation (Stage 3). The images were then reviewed by an experienced echocardiographer and the mitral and aortic annuli were segmented by selecting corresponding points in each of the 2D images (Fig. 2). Since the TEE transducer was spatially tracked, the acquired images and selected points corresponding to each segmented feature were retrospectively positioned according to their spatial stamp within a common 3D coordinate system. Ultimately the mitral and aortic valve annuli were reconstructed by connecting the selected points with 3D splines, leading to a pair of annuli at each of the three work-flow stages, for each of the four patients who have undergone the procedure to date.

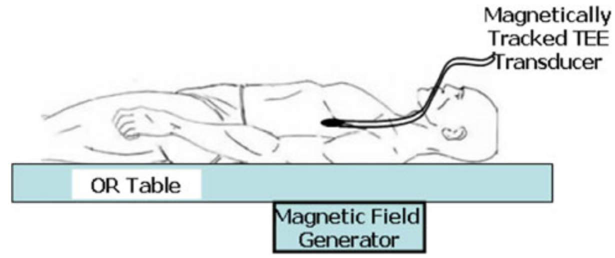

Fig. 1 Operating room setup showing patient on the OR table with the magnetically tracked TEE probe inserted in the oesophagus imaging the heart, and the magnetic field generator attached underneath the OR table

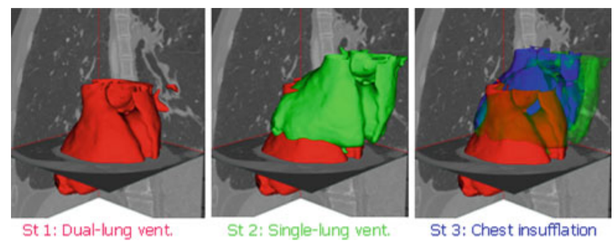

Fig. 2 Diagram showing an automatically-segmented epicardial surface model of a patient's heart mapped using the sequential stage-to-stage transforms reconstructed peri-operatively and displayed within the coordinate system of the pre-operative CT data. *Note*: Stage 1, 2 and 3 are displayed in red, green, and blue, respectively

To better interpret the displacement of the heart during the surgical workflow, the peri-operative data was transferred into the coordinate system of the original patient's CT dataset by aligning homologous features corresponding to the first peri-operative (Stage1) and the pre-operative (Stage0) datasets [5]. These two stages are physiologically equivalent given the same patient position and dual-lung ventilation, and hence minimal anatomical variations are expected. As a result, the peri-operative displacements can be estimated with respect to the principal body axes. The global motion of the heart was estimated according to the change in position of the centroid of the mitral and aortic valve annuli from Stage 1 to Stage 2 and to Stage 3.

In addition to estimating the valvular shift, we used the acquired information to identify morphological changes of the valve annuli across the three intra-procedure stages. Using principal component analysis and eigenvalue decomposition, we identified the three geometric principal axes of the annuli, which relayed information with respect to their orientation and geometrical changes (in-plane long- and short-axis length and out-of-plane normal vector) throughout the workflow. In addition, we also estimated the length of each annulus, as well as the centroidal distance and relative angle between the two annuli at each stage.

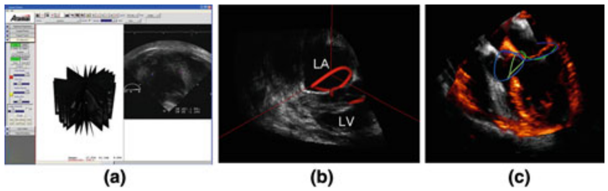

Fig. 3 (**a**) Acquisition of the tracked peri-operative 2D US images, which are then analyzed by a clinician to extract the features of interest (**b**) – mitral and aortic valve annuli; (**c**) Peri-operative US images of a patient's heart at Stage 1 and 2 showing the identified mitral and aortic valve annuli

Results

The movement of the heart from Stage 1 (dual-lung ventilation) to Stage 2 (single-lung ventilation) averaged to 24.0 ± 6.6 mm for the mitral valve and 32.7 ± 7.2 mm for the aortic; from Stage 1 to Stage 3 (chest wall insufflation), the mitral valve experienced a movement of 29.8 ± 6.8 mm, and the aortic movement averaged to 34.4 ± 8.7 mm. To display the overall movement, we used an automatically-segmented epicardial heart model animated using the peri-operative transforms to illustrate the position and orientation of the heart at the three stages (Fig. 3).

With regards to the feature morphology, the size of the valve annuli was on the order of 95 ± 8.3 mm for the aortic and 126 ± 9.6 mm for the mitral across the peri-operative work-flow. Moreover, the distance between the annuli centroids was recorded as 33.2 ± 5.8 mm, with a relative orientation angle of 46.1 ± 4.7 degrees. Given the insignificant morphological feature variations, a rigid-body registration may therefore provide sufficient to study the global migration of the heart during the workflow.

Conclusions

We have presented a technique used to estimate the overall displacement of the heart during the workflow associated with RA-CABG procedures. Our clinical results have suggested that the heart undergoes substantial migration due to the deflation of the left lung and the insuflation of the chest. These displacements cannot be ignored and this information should be employed to improve the pre-operative surgical plan and update the location of the target vessel, therefore better suiting the intra-operative anatomy. This information is critical for improved procedure planning and it constitutes the first steps towards the development of a robust technique that can predict the intra-operative target vessel location. Moreover, this work has the potential to reduce the rate of conversion [6] of the minimally invasive robot-assisted procedures to traditional open-chest surgery due to inadequate planning and difficulties in reaching the target.

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Dual-view 2D/3D registration for X-ray guided bronchoscopy

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Keywords Fluoroscopic navigation · Bronchoscopy · 2D/3D image registration · Dual-view surface mesh render · Distance map

Purpose

X-ray guided bronchoscopy is commonly used for targeting peripheral lesions in the lungs which cannot be visualized directly by the bronchoscope. The airways and lesions are normally not visible in X-ray images. As a result, transbronchial biopsy of peripheral lesions is often carried out blindly, which lowers the diagnostic yield of bronchoscopy. In response to this problem, we propose a registration method for X-ray guided bronchoscopy, allowing lesions and airways segmented from pre-operative 3D CT images to be superimposed onto 2D fluoroscopic images.

Methods

Although X-ray and CT images can be registered using a single X-ray view, accuracy and robustness are inferior to methods using multiple views. Dual-view 2D/3D registration may be clinically acceptable because one view can be obtained at the beginning of the interventional procedure, and the other view can be acquired during the procedure. Therefore, dual-view 2D/3D registration requires no significant change of standard workflow while offering the possibility of better accuracy and robustness. This paper describes a dual-view registration algorithm which involves the following steps:

Bone segmentation in CT and surface mesh generation

Bony structures (ribs, sometimes the spine) can be used in registration since they have good contrast in X-ray images and can be robustly segmented in CT images. The bones are first segmented in the CT image by applying an intensity threshold. Triangle surface meshes of the segmented bones are then generated. This step can be done offline.

Projection of surface mesh to two virtual image planes

Each triangle of the surface mesh is projected onto two virtual image planes. The positions and orientations of the virtual planes in the X-ray coordinate system are estimated poses of the fluoroscope intensifiers. The starting point of the registration can be obtained using prior knowledge of the patient's pose with limited manual adjustment. The surface projections on the two planes are two binary images, with pixels set to 1 if they are inside the projections of one or more triangles. The boundaries of the surface mesh projections are then extracted from the virtual 2D images and will be matched to the bone edges of X-ray images.