Computation of Coronary Perfusion Territories from CT Angiography

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Abstract

The assessment of myocardial viability in the left ventricle (LV) of patients with coronary artery disease is essential for determining prognosis and planning appropriate therapy. Typically, population-based models are used to associate regions containing non-viable (dead) myocardial tissue with a particular coronary artery. We propose a technique to automatically generate patient specific coronary distribution maps based on noninvasive multi-slice computed tomography (MSCT). We associate a region with the closest coronary using geodesic distance measurement over the LV epicardial surface. Projection of the coronary territories onto a flat disk allows our maps to be compared to standard models (i.e., the 17-Segment Model). This technique was applied to seven cases and an experienced cardiac radiologist examined the results for validation. Additionally, we register the patient-specific coronary territory maps with myocardial viability maps derived from noninvasive magnetic resonance imaging (MRI).

1. Introduction

Empirical models relating coronary arteries to underlying regions of left ventricular myocardium, such as the 17-segment model (see Figure 1) [1], are used routinely to describe the impact and severity of coronary artery disease. These population-based models have been shown to be accurate in large groups of patients and are a mainstay of interpretation of ultrasonographic, CT, MRI, and nuclear cardiac images. However, some studies have shown that these models are unable to take into account the clinically important variability in coronary anatomy between individuals. For instance, one recent study examined the accuracy of the 17-segment LV model in depicting the correspondence between coronary anatomy and regions of myocardium in 135 patients using monoplane coronary angiography [2]. The investigators found that the 17-segment model was accurate on average. However, in 27 patients (20%) there was discordance between the model and patient's anatomy in >4 segments. In 13 patients (10%) there was discordance in >5 segments; 8 of these patients had left dominant coronary distributions (the model assumes right dominance). Unfortunately, the clinical impact (if any) of these errors was not addressed in that study. In another study, co-registered MRI and MSCT images were used to assess the correspondence of individual patients' coronary anatomy (n=26) to a 17-segment coronary distribution model [3]. This study found that 22 patients were discordant in at least 1 segment (85%). Overall, 17% (76/442) of myocardial segments differed from their assignment by the 17-segment model.

To compute coronary territories, competitive region growing [5] was used in previous work [4]. However, it introduced a bias based on the order in which the regions expanded. In this study, we present a novel technique for deriving patient-specific coronary distribution maps from MSCT images by assigning a point on the surface to a territory based on the closest coronary.

2. Methods

In this study, validation of CT-derived coronary territory maps was performed using data from seven patients. All patients underwent both CT coronary angiography and selective x-ray coronary angiography at the Cleveland Clinic within 1 month of one another and with no interval surgical interventions (e.g. coronary bypass).

CTA was performed in each patient using either a 16 slice (n=2) or 64 slice (n=5) scanner (Sensation 16/64, Siemens Medical Solutions, Forcheim, Germany), and were reconstructed at 55-70% of the cardiac cycle. Contrast agent transit time was determined using a 10-20 milliliter (mL) timing bolus (Ultravist 300, Berlex, Wayne, NJ).

Furthermore, using data from 2 patients, we registered CT-derived coronary distributions maps with myocardial viability maps generated using a volume of delayed enhancement MR (DEMR) images, in order to determine the correspondence of dead tissue with the computed coronary territories.

2.1. Determining coronary territories

We assume the existence of a segmentation of the LV myocardium (including the LV center, and short axis and long axis normal orientations), as well as labeled segmentations of the coronary vessels (Left Anterior Descending (LAD), Left Circumflex (CFX), Right Coronary Artery (RCA) and their associated branches).

A 3D polygonal triangulation model in the shape of an ellipsoid with a recursive geodesic tessellation level of 6, is scaled and projected on to the myocardial surface, which is obtained from an offline segmentation of the CT angiogram (CTA) volume to form the LV surface $\boldsymbol{S}$.

The labeled coronary segmentations are projected onto $\boldsymbol{S}$ using the closest point method. For each node of $\boldsymbol{S}$, we compute the shortest path (the geodesic distance over the surface) using Dijkstra's algorithm [6, 7] to each of the projected coronary segmentations and associate that node with the closest projected coronary.

The nodes of $\boldsymbol{S}$ are expressed in spherical coordinates $\boldsymbol{S}(\phi, \theta)$ and are projected onto a 2D disk, $\boldsymbol{D}$ in polar coordinates $\boldsymbol{D}(r,\theta)$ via:

$$\phi : [-\pi/2, \pi/2] \rightarrow r\,[0,1] \qquad (1)$$

In order to omit the valve plane we allow ϕ to range from $-\pi/2$ at the apex of the LV to $3\pi/8$, just before the mitral valve. The projected disk, $\boldsymbol{D}$, is then colored based on the classification of the nodes forming the territories.

2.2. Validation of computed coronary territories

To validate the CTA-derived models, we used the Green Lane method, a systematic technique for assigning coronary arteries to specific myocardial regions, which has been previously described [8] and recently applied to tomographic imaging [9]. An expert cardiovascular imager manually transcribed each patient's coronary arteries, including branch vessels, onto a standard diagram, thus preserving the relative size and distribution of each vessel while allowing anatomical variation between patients. This technique is demonstrated schematically in Figure 1.

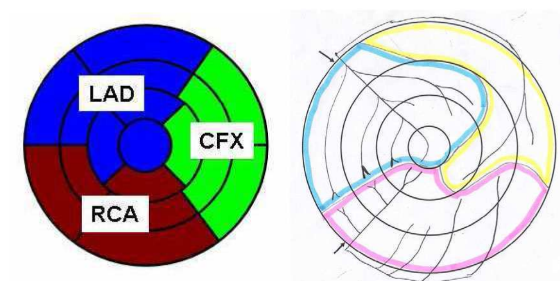
From the segmentation of the myocardium in a corresponding DEMRI study [10], where dead or damaged tissues, (possibly caused by myocardial infarction) display increased signal intensity, we mapped a computed maximum intensity of the myocardial tissues onto $\boldsymbol{S}$. We then project from 3D spherical coordinates to 2D disk coordinates using (1) and register the two datasets manually, by aligning the septal insertion points and apex. We expect bright regions to be found in the territory fed by a blocked coronary.

3. Results

Figure 2 demonstrates CT-derived coronary distribution maps from 2 patients, along with the corresponding x-ray angiography derived ground truth maps. In addition, the generic 17-segment model is included for comparison.

To determine the relative correspondence between the CT-derived maps and the ground truth maps, the maps from each patients were aligned spatially and the area of correspondence (on a pixel basis) was computed. Results are shown in Table 1. Overall, the average percent correlation between CT-derived maps and the ground truth was 84%. Using this same approach, we compared the 17-segment model with the ground truth maps; in this case, the average correlation was 79%.

In Figure 3 we present the registration of CT-derived maps to DEMRI studies in 2 patients. In DEMRI, dead or damaged regions exhibit increased signal intensity. From the coronary angiography studies these patients underwent, we know the condition of their coronary vessels. Our maps accurately predict the location of damaged tissues based on the information from the coronary angiograms.



(a) (b)

Figure 1. (a) The 17-Segment Model: cross sections of the LV perpendicular to long axis (apex, apical, mid and basal portions). The septum is to the left. Three regions are found to be typically irrigated by the Left Anterior Descending (LAD), the Left Circumflex (CFX) and the Right Coronary Artery (RCA). (b) Green Lane Method: an experienced cardiac radiologist manually transcribes the coronary tree, with branch vessels, from a coronary angiogram onto a bull's eye plot. The plot is then divided into coronary distribution regions based on these projections (LAD blue, CFX yellow, RCA pink).

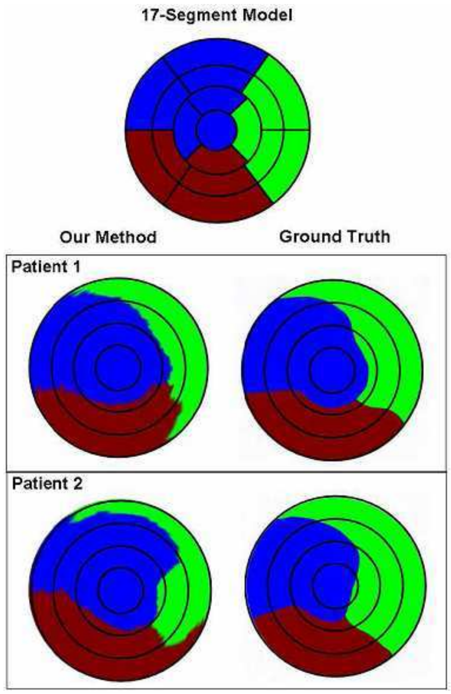


Figure 2. Comparisons of results for two patients. Top: The 17-Segment Model. Left: Our method. Right: Ground truth maps based on the Green Lane method applied to coronary angiography. In all cases, blue denotes myocardium supplied by the LAD artery, green by the CFX artery and brown by the RCA artery.

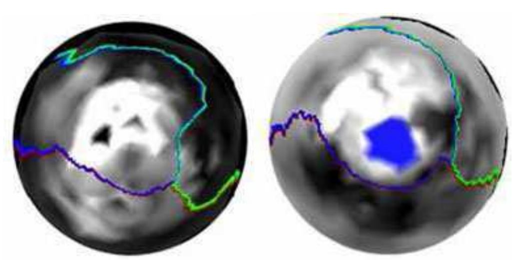


Figure 3. Coronary Territory maps registered with DEMR functional images. Boundaries between myocardial territories are denoted by colored lines: blue/green separates the LAD and the CFX territories, blue/brown separates the LAD from RCA and green/brown separates CFX and RCA. Left: Patient with 100% blockage of the LAD, no significant stenosis of the CFX, and 70% blockage of the RCA, reflected in the bright regions in the LAD territory with mildly increased signal intensity in the RCA territory. Right: Patient with occluded mid/distal LAD. No significant coronary disease was found in the CFX or RCA. The blue region in the center of the figure exists because the apical "cap" was not covered by the DEMR images.

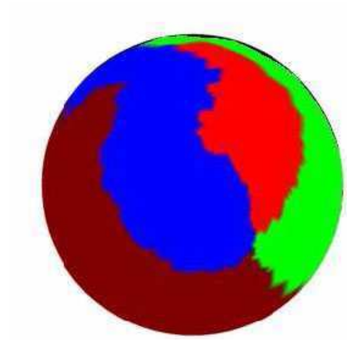


Figure 4. Our approach allows a flexible number of territories dependent upon patient characteristics. In this patient, myocardial regions perfused by a large diagonal branch of the LAD (red) are displayed separately from the LAD proper (blue), RCA (brown) and CFX (green) territories.

Table 1. Comparison on a per patient basis of our technique versus the 17-Segment Model using the Green Lane method on coronary angiography as the ground truth. Results indicate the percentage of myocardial pixels which agree between the techniques being evaluated. (p value .10).

Patient	Our Method vs. Ground Truth (%)	17-Segment vs. Ground Truth (%)
Patient 1	97.1	79.1
Patient 2	81.4	81.7
Patient 3	83.5	73
Patient 4	78.1	81.1
Patient 5	87.2	78.7
Patient 6	78.3	77.7
Patient 7	84.8	81.4
Average	84.3	79.0

4. Discussion and conclusions

One strength of our method is that it is not limited to the standard three territories. In many cases, inter-patient differences in coronary anatomy may cause a branch vessel to take on added significance. Our approach allows us to create as many territories as there are individual vessels visible in the CT images. Figure 4 illustrates an instance where an LAD (diagonal) branch is responsible for irrigating a region normally fed by the CFX. Our maps may be tailored to the specific characteristics of the patient.

Although we certainly believe that developing a patient-specific approach to relating coronary anatomy with the underlying LV myocardium represents an improvement over using empirically derived models, we also recognize several limitations inherent in our approach as well as with our validation. First, our approach is limited by the spatiotemporal resolution of CT image acquisition (primarily temporal). The specification of myocardial regions is dependant upon a complete segmentation of the coronary tree, including branch vessels. However, complete visualization of small branch vessels, in particular the perforator vessels that supply the septum, is not currently possible with CTA to the extent that it is using coronary angiography. However, temporal resolution has decreased from approximately 250 msec to less than 100 msec over the past 3-5 years, so we anticipate the improvement of new generations of CT scanners.

In addition, there is inevitable distortion of the cardiac base during the flattening process of creating the patient-specific models. Distortion of the anatomical structures is introduced by the projection of a 3D texture onto a 2D frame, bringing stretching to the latitude rings projected onto the rings of the map.

Lastly, there are limitations with the Green Lane technique used for validation of our CTA-derived models. The LV myocardium is not visualized using coronary angiography. Thus, the Greene Lane technique represents a "best guess" by the physician as to the relationship between the coronary arteries and the underlying myocardium. However, this technique still represents one of the only systematic and validated methods for depicting this relationship. Furthermore, it mimics the mental integration of imaging data from disparate sources that has become clinical standard of cardiovascular care world-wide. Thus, we felt it was an appropriate validation method.

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