Published in final edited form as:

Crit Pathw Cardiol. 2008 September ; 7(3): 185–190. doi:10.1097/HPC.0b013e318178eaa5.

Potential Uses of Computed Tomography for Management of Heart Failure Patients With Dyssynchrony

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Abstract

Cardiac resynchronization therapy has become an integral part in the step-care approach to manage patients with heart failure. Cardiac imaging remains central to appropriate patient selection and optimal left ventricular lead placement, both of which are important determinants of response to cardiac resynchronization therapy. One of the biggest limitations with current imaging modalities is the inability of a single technique to address each, the anatomic (venous anatomy), mechanical (dyssynchrony), and structural (extent of scar location) issues accompanying cardiomyopathy. We present here the potential concept of using cardiac computed tomography as a single modality to acquire functional and anatomic information, and also to show the possibility of integrating this with real time fluoroscopy.

Keywords

cardiac resynchronization therapy; computed tomography; dyssynchrony; left ventricular lead placement; heart failure; coronary veins

Heart failure, coronary veins Heart failure (HF) is one of the leading causes of morbidity and mortality in the United States with 50% mortality at 5 years.^{1,2} Cardiac resynchronization therapy (CRT) has improved clinical outcomes for patients with refractory congestive HF, left ventricular (LV) systolic dysfunction, and wide QRS duration.^{3–5} However, about 30% of patients who have received CRT did not respond favorably and had either no improvement or worsening of symptoms.^{6–8}

Noninvasive cardiac imaging has the promising potential of determining appropriate patient selection and optimal LV lead placement, both of which are critical determinants of response to CRT. However, because most of the imaging modalities provide complementary information regarding cardiac structure (eg, fluoroscopy for coronary venous anatomy) and function (eg, echocardiography [Echo] for mechanical dyssynchrony), combining some of these technologies may help improve the diagnosis and facilitate planning the treatment and delivery of the pacing therapy in patients receiving CRT. There are data from small retrospective studies, which have shown that pacing over the site with maximal discordance^{9–11} and avoiding a region of scar^{12–16} may result in a better outcome. Current use of intraprocedural echo to demonstrate the most delayed segment to guide LV lead

placement is cumbersome and technically challenging. Hence, preprocedural evaluation of mechanical dyssynchrony and intraprocedural integration with venous mapping may be a useful strategy, but still needs to be developed and tested prospectively. Moreover, the errors pertinent to integrating information from 2 or more different imaging modalities (ie, x-ray, echo, and cardiac computed tomography [CT]) may be magnified when compared with acquiring the information from a single imaging modality.

Multidetector CT (MDCT) has the potential to provide important information pertinent to (1) the coronary venous anatomy, ie, distribution of tributaries, patency and luminal size of the coronary veins, (2) LV contractile function, (3) localization of scar, (4) mechanical dyssynchrony, and (5) integrated information regarding the relation of the venous branch with the segment of dyssynchrony and/or scar. Herein, we present the potential concept of using CT as a single modality to acquire functional and anatomic information, and also to show the possibility of integrating this with real time fluoroscopy.

METHODS

CT-Venography

The coronary sinus and venous tree with its secondary and tertiary tributaries can be well visualized by MDCT.^{17–23} The CT imaging protocol is nearly similar to that used for a standard coronary CT angiography, with several exceptions. A test bolus protocol is preferred over bolus tracking to calculate the contrast agent transit time. For optimal enhancement of the coronary venous system, an empiric 5 to 10 seconds delay should be added to the time to peak contrast opacification of the ascending aorta so that image acquisition will be performed during the venous and not arterial phase.

The patient shown in Figure 1 was being considered for LV lead revision and referred for MDCT to assess his coronary venous anatomy preprocedurally. He was a 74-year-old gentleman with ischemic cardiomyopathy who had both clinical and echo deterioration after receiving his biventricular device and considered a CRT nonresponder. Both of his ventricular leads showed elevated thresholds with loss of LV lead capture. The surface ECG QRS duration was prolonged (200 milliseconds) and an echo demonstrated inferoposterior akinesis with significant intra- and interventricular dyssynchrony.

To accurately delineate the coronary venous anatomy and patency before replacing the leads, an ECG-gated contrast-enhanced 64-slice coronary MDCT (Sensation 64, Siemens Medical Solutions, Forchheim, Germany) was performed with the following parameters: 0.6mm slice thickness, 120 kVp, 850 mAs, gantry rotation time 330 milliseconds. Image reconstructions of the dataset were reconstructed at 0.75-mm section thickness with 0.4-mm section overlap using B26 smooth reconstruction kernel. Volume-rendered 3-dimensional (3D) CT of the coronary venous tree (Fig. 1A) was reconstructed from the best phase of the cardiac cycle using commercially available software (Leonardo, Siemens Medical Solutions, Forchheim, Germany). The corresponding intraprocedural coronary venous angiography (Fig. 1B) demonstrated excellent matching of the coronary venous tree with CT, which facilitated the revision and placement of the LV lead along the lateral wall in the mid-LV region.

One month after lead revision, the patient had both significant clinical improvement and echo changes with improved intra- and interventricular synchrony and reverse LV remodeling. This case illustrates the potential applicability of preprocedural CT for the assessment of coronary venous anatomy to aid with LV lead placement.

CT-Dyssynchrony

A CT can now be used to quantify LV dyssynchrony from evaluation of changes in wall thickness over time.²⁴ This approach is illustrated in Figure 2, using short axis stacks of the left ventricle, functional data over time can be evaluated using multiphase reformats reconstructed at a user-defined percent increment of the cardiac cycle. Visually, from the wall thickness-time graphs, the different segments from the HF patient with dyssynchrony (Fig. 2D) contract nonuniformly, whereas the comparable segments from the normal subject (Fig. 2C) appear to thicken uniformly at the same time early in systole. A dyssynchrony index can be calculated as the mean of the standard deviations of the time to maximal systolic wall thickness of each of the 6 standardized segments from the basal to apical levels. More variability between the times to maximal wall thickness of each segment may reflect a greater degree of dyssynchrony. The clinical validity of this method needs further prospective clinical evaluation.

CT-Contractile Function/Scar Localization

Using dedicated software to create 3D LV models for the assessment of regional wall thickening and percentage wall thickening, additional information on contractility and regional functionality can be obtained. We are able to manually coregister the anatomic and functional information by superimposing regional LV functional data (ie, graphic display of percentage wall-thickening) onto the volume-rendered 3D CT dataset, which contains the coronary vein topography (Fig. 3). This CT coregistration model can provide information on the location of coronary veins and its proximity to regions of scar, which should be avoided during lead implantation. Because CRT procedures are aided by fluoroscopy, these angiographic images can be subsequently used for coregistration with the coronary venous tree from cardiac CT to optimize lead placement, though better coregistration software needs to be developed to facilitate its general applicability.

DISCUSSION

CRT facilitates ventricular synchrony through stimulation of the late contracting regions of the left ventricle. So far, the approach for lead positioning has been rather simplistic and has been mostly directed at placement of the lead along the lateral wall of the left ventricle.^{25,26} Recent work has suggested that positioning the LV lead in the segment away from scar tissue^{12–16} or directly pacing over the segment of maximal mechanical dyssynchrony^{9–11} may be a more appropriate strategy to improve clinical outcomes. Multimodality imaging that merges functional with anatomic information may facilitate such an individualized approach, by helping to proactively target the most reasonable region. As described above, a more practical strategy would involve using a single imaging modality (such as CT), which could provide all the necessary information, pertinent to the venous anatomy, mechanical dyssynchrony, and contractile function.

The current approach to evaluate the coronary venous system involves the use of intraprocedural retrograde venography, using a balloon occlusion technique.²⁷ Recent reports have suggested that MDCT might be a useful technique to obtain high quality 3D images of the cardiac venous system.^{17–23} Technical progress on this front has enabled higher spatial resolution with a decreased acquisition time, and detailed delineation of the coronary venous tree. Suboptimal enhancement of the second and third order tributaries of the coronary sinus remains a problem and this is largely dependent on operator experience in performing the scanning procedure. Besides the tributary size, the other determinants of the quality of the CT venogram include: using a test bolus to facilitate the scanning procedure, patient's hemodynamic status, ie, circulation time, and operator experience in segmenting coronary veins. Recent advances in the newest CT technology now provides a spatial

resolution of 0.4 mm, which is comparable to that of invasive coronary angiography (0.2 mm), can provide a much more detailed topography of the venous tributaries over the LV wall.²⁸ CT venography enables preprocedural assessment of the coronary venous anatomy, which in turn allows the implanting physician to assess the potential feasibility and success of the procedure. In some circumstances, it may be more appropriate to place the LV lead via a surgical epicardial approach. In a minority of cases, CT provides the potential advantage of visualizing the phrenic nerve and thereby may help positioning the LV lead to avoid diaphragmatic pacing.²³

Several noninvasive imaging modalities have tried to establish a reliable measurement of LV dyssynchrony that would correlate and predict CRT response. Of the noninvasive modalities for dyssynchrony analysis, 2-dimensional (2D) echo has been most extensively studied but its clinical applicability has been limited because of conflicting results.^{29–35} Most recently, results from a multicenter study found that no single 2D echo parameter was able to reliably predict CRT response.³⁶ Although a few feasibility studies with 3D echo, nuclear, and cardiac magnetic resonance imaging show potential, they remain investigational and are limited by inherent variables, such as operator dependence, poor spatial resolution, and device incompatibility, respectively.^{37–42} The role of CT in evaluating dyssynchrony may emerge with the advent of newest CT technology, which has improved temporal resolution, in a range comparable to echo and cardiac magnetic resonance.⁴³ The high spatial resolution of 0.4 mm is capable of visualizing the coronary venous anatomy in detail whereas the improved temporal resolution of up to 42 milliseconds (mean temporal resolution of 60 milliseconds) may enable more precise temporal-related functional evaluations such as the assessment of LV dyssynchrony and the detection of regional LV dysfunction as a result of myocardial scar.⁴³

Although most CRT procedures are currently being aided by 2D fluoroscopic imaging (venography using multiple 2D projections), rotational contrast venography (Philip Allura FD 10) is an alternative that offers a multiangle visualization of the coronary venous anatomy.¹¹ The heart is imaged continuously over a 110 degree rotation in 4 seconds at 30 frames/s with a single injection of contrast. The rotational images can then be reviewed over a full range of angles, providing the implanting physician with detailed information of the origin, course, and tortuosity of each branch. This provides the different options regarding sites and the type of LV lead to be implanted. Recent efforts have been directed at real-time reconstruction of three-dimensional models of the coronary venous tree with CT, 3D coronary venous angiography, and x-ray (Fig. 4) to give more information regarding the size of the coronary sinus, its main branches and second-order tributaries. This information should prove useful both to define an individual patient's coronary venous anatomy and to tailor an LV lead implant strategy, which targets a myocardial segment of interest. Although CT is not practical during lead placement, as a preprocedural tool it can resolve the LV myocardium throughout the cardiac cycle that makes it possible to assess myocardial function and differentiate regions of scar from regions of normal function. Moreover, CT can resolve the 3D coronary vasculature, which can facilitate coregistration of CT data to 3D venogram using fiducial points from the coronary sinus ostium and body. Unique methods of data acquisition, processing and display are needed to facilitate the image integration process. The modeling procedure is multilayered and requires processing strategies, which include segmentation, registration, followed by integration.

The ability to integrate CT with x-ray has many advantages. Firstly, it may not be necessary to perform a detailed intraprocedural venogram, and merely opacification of the main coronary sinus trunk may enable complete registration of the fluoroscopic image with the CT venogram. Alternatively, there will be instances, where the CT venogram may be suboptimal, and registration with the fluoroscopic image (rotational venogram) may provide

all the necessary venous anatomy information superimposed on the functional data obtained from the CT.

Many unresolved issues pertinent to CT persist. It is still unclear if there is any clinical benefit to prospectively performing preprocedural CT scans in patients scheduled to undergo CRT implants. Currently, it should be still considered investigational, although we gain more experience with the technology. Using CT in screening CRT candidates for a suitable coronary venous anatomy for the transvenous approach may be limited in patients with atrial fibrillation and other types of irregular heart rhythm, such as frequent premature atrial or ventricular beats. Another major concern related to the use of CT is the relatively high radiation dose exposure reaching 15 to 20 mSv per scan. Recently, however, newest CT scanners with improved detection and reconstruction algorithms have allowed cardiac CT scanning to be performed with dose exposure in the range of 1 to 5 mSv.⁴⁴ Additionally, CT is not practical as an imaging modality for follow-up and device optimization in this patient population. The true value of this single-modality imaging strategy would be dependent on its ability to enhance the success rate of device implantation, shorten implantation time, and guide lead placement for optimal clinical response, all of which will need prospective evaluation.

Acknowledgments

The authors thank Arash Aryana, Robert Manzke, Raymond Chan, and Mark Handschumacher for their contributions.

Supported by NIH grant 5T32HL076136 (to Q.A.T.); Research grants, Consulting and Lecture honoraria from Biotronik, Boston Scientific, Medtronic and St. Jude Medical (to J.P.S.).

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FIGURE 1.

A, Volume-rendered 3D reconstruction from MDCT showed the LV lead in the AIV with partial perforation, 2 patent venous branches draining the lateral wall (2 and 3), and a small patent posterolateral branch.¹ B, Corresponding intraprocedural coronary venous angiography demonstrated excellent matching of the coronary venous tree. CS indicates coronary sinus; GCV, great cardiac vein; AIV, anterior interventricular vein; MCV, middle cardiac vein.

FIGURE 2.

A, Model of endocardial (red) and epicardial (green dots) left ventricular shells demonstrates how short axis slice of the left ventricle can be obtained by MDCT. B, Using multiphase reformats reconstructions, wall thickness data over time can be evaluated by defining the endocardial (red circle) and epicardial (green circle) boundaries at different phases of the cardiac cycle. C, D. Examples illustrating wall thickness over time of 6 standardized myocardial segments (inferoseptal, anteroseptal, anterior, anterolateral, inferolateral, inferior) at a midventricular slice are graphically depicted in a normal patient (C) and a heart failure patient with Echo evidence of dyssynchrony (D).

FIGURE 3.

A, Volume-rendered 3D reconstruction of the contrast enhanced CT dataset depicting the coronary venous anatomy from the same heart failure patient in Figure 2D. B, Graphic display of percentage systolic wall thickening of the left ventricle shows an area of scar or no wall thickening (purple). C, Coregistered CT anatomy and functional data can determine whether a coronary vein overlies a region of scar. The purple region indicates an area of 0% wall thickening; representative of scar and thereby, should be avoided during lead implantation. Given the option of a coronary vein overlying scar (arrow) and one that overlies myocardium that thickens (arrowhead), LV lead placement should be guided towards the vein that overlies nonscar myocardium. This coregistration method with preknowledge of the coronary venous tree and location of scar by CT may ultimately be used for preprocedural lead placement strategy.

FIGURE 4.

Real-time reconstruction of three-dimensional coronary venous model with CT, 3D coronary venous angiography, and x-ray provides more information regarding the size of the coronary sinus, its main branches and second-order tributaries.