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Cardiac CT: Imaging of and Through Cardiac Devices

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Abstract

For patients with cardiac devices, cardiac computed tomography (CT) remains the mainstay for imaging due to its superior resolution as compared with echocardiography and nuclear studies and no contraindication to metal as with cardiac magnetic resonance imaging. This review focuses on the evaluation and pitfalls of coronary arterial imaging in patients with devices, such as pacemakers, implantable defibrillators, cardiac resynchronization therapy (CRT), as well as complications such as lead perforation and safety concerns of CT interference. We discuss both pre- and post-procedural CRT assessment for coronary venous imaging and pre-procedural myocardial scar assessment to localize regions of scar and peri-infarct zone to facilitate ventricular tachycardia ablation in patients with devices. We describe potential new research on dyssynchrony and integration with myocardial scar and site of latest activation for patients with or being considered for CRT. We detail the utility of CT for the assessment of proper function and complications in patients with left ventricular assist device implantation.

Keywords

Cardiac CT; Pacemaker; Defibrillator; Cardiac resynchronization therapy; Left Ventricular assist device

Introduction

Current guidelines and statements recommend several indications for non-invasive coronary angiography using multi-slice computed tomography (CT) for the evaluation of coronary artery disease [1]. For patients with cardiac devices, metal artifacts can potentially lead to invaluable assessment of the coronary arteries, and there are known complications, such as lead perforation as well as the rare possibility of CT interference. There are some indications for cardiac CT within electrophysiology, such as coronary venous system imaging in patients considered for cardiac resynchronization therapy (CRT). There is active research in the utility of CT in the assessment of myocardial scar and left ventricular (LV) dyssynchrony, important factors in consideration for CRT. Contrast-enhanced CT with first-pass perfusion, delayed enhancement, and newer dual-energy acquisitions allow for tissue characterization of LV myocardium and identification of myocardial scar, and the potential integration of such information into clinical mapping system has facilitated substrate-guided ventricular tachycardia ablation. As left ventricular assist devices (LVAD) have become more widely used for patients with severe heart failure as destination therapy, or as a bridge

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to myocardial recovery or transplantation, there is also increased use of CT in the assessment of function and complications after LVAD implantation.

Coronary Artery Evaluation

In patients with implantable devices such as pacemakers, implantable cardioverter-defibrillators (ICD) or CRT, the use of cardiac CT faces several limitations in the evaluation of coronary artery disease [2]. The appropriate use criteria and other cardiac CT guidelines have not addressed the usefulness of coronary artery imaging in patients with implantable devices due to the scarcity of data regarding non-invasive coronary angiography performance in the presence of implantable cardiac devices.

Only a few reports exist that focus on CT in patients with implanted devices [3–5]. Pacemaker and implanted ICD leads prevented a valid interpretation of images in up to half of the patients [3]. Streak artifacts arise from metal active elements of pacemaker or ICD leads near the myocardium and are a result of 2 processes—a beam hardening phenomenon due to dense metallic component as well as objects blooming through edge-gradient effect due to disparity between the high-density metal and the low-density surrounding blood [6]. Pacing leads typically have an electrode pair at the tip for sensing and pacing. ICD leads also have similar pacing electrodes at the tip but additionally have shock coils in the superior vena cava and the right ventricle (RV). Despite the small size of the electrodes and shock coils, they create substantial streak artifacts in the CT images. The central conductor wires are insulated with silicon and usually well visible, but they are less dense than the electrodes and do not cause noticeable artifacts or streaking. Lack of insulation of the tip and its much larger active surface can have a different influence on image quality, and hence artifacts seem to originate mostly from the tip rather than the body of the lead. The ICD shock coils can cause significantly larger artifacts than the smaller pacing lead electrodes, extending across multiple image slices. The artifacts most likely affect the inferoseptal region of the LV, as ICD shock coils typically are placed in the RV near that region. Depending on the electrode design, such as metal composition, wire thickness, and coil dimensions, certain shock coils produce more intense artifacts than others. In addition, the extent of artifacts may also be affected by lead position, CT acquisition parameters, patient girth, respiratory, and cardiac motion. Other metal objects of similar size and density, such as sternal wires and surgical clips tend not to cause metal artifacts.

The presence of endocardial leads may limit cardiac CT evaluation of all 3 coronary arteries (Fig. 1) and reported to occur in 29 %–61 % of the cases [4, 5]. The atrial lead has a destructive influence on the image quality of right coronary artery visualization. In CRT, the LV lead can have a strong destructive influence on the left circumflex visualization, particularly at the atrioventricular groove. In addition to the metal artifacts, the ECG gating process has also been identified as another cause of image artifacts [5]. In pacemakers with unipolar leads, reconstruction of images may be affected by inappropriate gating due to double counting of the high voltage unipolar pacemaker ‘spikes’. Leads with bipolar pacing do not pose such issues in cardiac CT studies with ECG gating.

Perforation of Implantable Leads

One of the complications of pacemaker and ICD implantations is lead perforation with an incidence of less than 1 % [7] (Fig. 2). While this often presents acutely during implantation, it can also have a delayed presentation. Late perforation is defined as lead perforating through the myocardium more than 1 month after implantation, and is often underdiagnosed and associated with significant morbidity and potentially catastrophic consequences. The usual work-up of suspected lead perforation includes device interrogation, chest radiography, echocardiography, and fluoroscopy. Echocardiography usually provides clear

visualization of the lead tip and the combination of these modalities will give a definitive diagnosis in most cases.

In cases where echocardiographic findings are equivocal, CT can be a helpful adjunct to echocardiography in the diagnosis of lead perforation. Few reports have been published evaluating mostly the efficacy of CT for visualization of lead perforation. In one series of asymptomatic patients with pacemakers or ICDs, late lead perforation was reported to occur in 15 out of 100 patients with chest CT as incidental findings [7]. However, the precise location of the lead tip or even such findings can be missed due to streaking artifacts and acoustic shadowing from the metallic lead. In many instances, near perforation might be detected on CT where the lead tip is seen close to the epicardium, but the implications of such findings are less clear, especially in patients without any associated symptoms, pericardial effusion, or abnormalities in lead interrogation. Such CT findings alone are not an indication for lead removal, but increased vigilance during follow-up may be indicated.

CT Interference on Cardiac Devices

Pacemaker interference associated with irradiation has been reported in patients receiving radiotherapy, and high-dose irradiation can produce unnecessary electric currents within the semi-conductor circuit used in the current generation of pacemakers [8]. However, at the dose levels associated with diagnostic examinations that involve x-rays, radiation levels have been considered to be below the threshold where interference with implantable devices will occur [9]. In 1 study where 21 patients with pacemakers or ICDs were exposed to ionizing radiation from CT systems, in both spiral and dynamic acquisition modes at typical and maximum dose levels, devices were monitored during exposure to check for any operational abnormalities and were interrogated after exposure to check for any residual abnormalities [10]. CT irradiation at typical clinical doses may lead to oversensing of implantable devices in most devices tested, although the identified effects are predominantly transient and cease after the device stops moving through the x-ray beam or the beam is turned off. No programming change or permanent change to device is observed. For pacemakers and ICDs with anti-tachycardia features, oversensing introduces extrasenses that may simulate an atrial or ventricular arrhythmia and cause false detection and delivery of an unnecessary therapy. Since the dwell time of the radiation over the electronics module in the pulse generator will be less than 1 second for a typical CT study, the effect on oversensing is transient and the probability of an ICD shock is extremely low [10]. The general conclusion is that it is safe for patients with implantable devices to undergo CT studies if the device moves briefly through the x-ray beam in sequential or spiral scanning. Effects are likely brief with no lasting consequences. The historic absence of adverse reports regarding patients with devices undergoing CT implies a general level of safety in these applications. In our experience, there have been no adverse effects on devices during cardiac CT scanning.

Coronary Venous Imaging

CRT with biventricular pacing is an effective treatment for certain patients with heart failure by improving the synchronous contraction of both ventricles, leading to improved hemodynamics and ejection fraction [11]. LV pacing is accomplished via the coronary sinus (CS) but the presence of a suitable branch of the CS is important for LV lead positioning with a transvenous approach [12]. Major components of the coronary venous system include the CS, great cardiac vein (GCV), posterior vein of the left ventricle (PVLV) or posterolateral vein, left marginal vein (LMV) or lateral vein, anterolateral vein (ALV), and anterior inter-ventricular vein (AIV). The great cardiac vein courses alongside the left circumflex artery and subsequently drains into the CS. It receives several branches including

the LMV, which courses along the lateral border of the LV, and the PVLV. These are often the target veins for pacemaker lead placement in CRT (Fig. 3). Inability to deliver CRT was about 10 %, due mainly to failure to cannulate CS or cardiac veins [13]. Previsualization of the coronary venous system before LV lead implantation might help identifying some anatomical aspects before CRT implantation, such as the variability of the CS ostium including its size and angle of entrance, the number of target coronary veins [14], the presence of the Thebesian or Vieussens valves [15], presence of vein of Marshall, luminal narrowing due to a crossing artery, along with ventricular remodeling that may influence the shape and size of the heart [16].

Currently, the most common technique used to evaluate the coronary venous system is retrograde venography, obtained invasively by direct manual contrast injection and occlusion of the CS. Multiple studies have shown excellent agreement between CT of the coronary venous tree and invasive retrograde venography [17–20]. Technical advances have enabled higher spatial resolution with shorter acquisition time, and detailed delineation of the cardiac venous tree, but the methods need to be standardized in order to provide images most useful during lead implantation [21]. In 74 % of the patients, it was possible to obtain very similar images to those during CRT implantation. The CS was clearly visible in all cases and at least one vein was clearly visible in the target area for CRT in 95 % of cases. Among the target veins, the PVLV or posterolateral vein was visible most frequently, followed by the LMV (or lateral) and anterolateral veins. Suboptimal enhancement of the second- and third-order branches of the CS remained challenging and largely dependent on operator experience in performing the CT venogram. The optimal phases of the cardiac cycle for the visualization of the cardiac venous system are best in the systolic phase due to high venous flow during systole, making the cardiac veins larger and easier to identify [22]. In some circumstances when there are no suitable veins for a transvenous approach, it may be more appropriate to place the LV lead via a surgical epicardial approach or not undergo CRT implantation at all [12]. The visualization of all the structures surrounding the heart is also important, such as phrenic nerve and diaphragm, and thereby may help positioning the LV lead to avoid diaphragmatic pacing [23] though in our experience the phrenic nerve is not easily visualized.

Myocardial Scar Localization of Infarct and Peri-Infarct Zone

Quantification of myocardial scar by contrast-enhanced CT using first-pass perfusion and late delayed enhancement has been shown to correlate well with findings of myocardial scar and viability in cardiac magnetic resonance imaging (CMR) [24•] (Fig. 4). It may be used as an alternative for those with devices and contraindication to CMR. There is also increasing experience on the use of dual-energy CT in assessing quantitative myocardial perfusion and scar detection in patients with chronic coronary artery disease [25, 26]. Contrast-enhanced CT can provide comprehensive characterization of LV anatomy and myocardial scar including anatomic, dynamic and perfusion imaging. Integration of reconstructed 3-dimensional scar data into clinical mapping systems has the possibility to facilitate substrate-guided ventricular tachycardia ablation [27].

Research in Myocardial Scar, Dyssynchrony, and Co-Registration of Imaging in CRT

Given the high non-response rate (~30 %) to CRT using current implantation strategy, combining information regarding cardiac structure and function may help improve the diagnosis and facilitate planning the treatment and delivery of the pacing therapy in patients receiving CRT. Among the issues that remain inadequately studied is LV lead positioning,

optimally pacing over the site with maximal discordance, and avoiding a region of myocardial scar may result in better outcome [28, 29].

Integrating information provided by transthoracic echocardiography and CT has been used as a strategy in planning LV lead insertion for CRT implantation [30]. Segmental echocardiographic data are loaded into the corresponding CT segments. The integrated image places either static or dynamic multi-dimensional assessment of LV mechanical activation into the context of contiguous anatomy. Contiguity to the region of latest mechanical activation may favor lead implantation by one vein over another. Similarly, contiguity to a large region of scar or left phrenic nerve may reduce the attractiveness of an otherwise anatomically favorable vein. However, the concurrent use of echocardiography intraprocedurally to demonstrate the most delayed segment to guide LV lead placement is technically challenging.

CT has the potential to provide preprocedural evaluation of the coronary venous anatomy, LV contractile function, localization of scar, mechanical dyssynchrony and integrated information regarding the relation of the venous branch with the segment of dyssynchrony and/or scar. CT may potentially be used to quantify LV dyssynchrony from evaluation of changes in wall thickness over time, though clinical correlation is still needed [31]. Newer CT technology, with improved temporal and spatial resolution, may allow more precise function evaluation such as the assessment of LV dyssynchrony and the detection of regional LV dysfunction as a result of myocardial scar.

The possibility to combine CT and fluoroscopy may be helpful in facilitating CS cannulation as well as enabling navigation within CS and cardiac veins to the appropriate location. Feasibility of registration of 3D CT-based images with projection images obtained using fluoroscopy has been demonstrated [32]. This registration accuracy for both CS main body and cardiac veins was extremely high. Overall this fusion imaging allows constant comprehensive display of CS body and branches for guiding CRT implantation and potentially reducing complication rates [30, 33]. A detailed intraprocedural venogram may not be necessary and merely opacification of the main CS trunk may enable complete registration of the fluoroscopic image with the CT venogram. Registration with the fluoroscopic image may provide all the necessary venous anatomy information superimposed on the functional data obtained from the CT. The clinical validity of this method still needs further prospective clinical evaluation. Current research is being undertaken to evaluate the ability of CT to enhance the success rate of device implantation, shorten implantation time and guide lead placement for optimal clinical response.

CT of Left Ventricular Assist Devices

Left ventricular assist devices (LVAD) are typically implanted as a bridge to myocardial recovery or heart transplantation or as destination therapy and improve clinical outcomes [34–38]. LVADs typically fall into 2 categories: pulsatile flow and continuous flow. Pulsatile flow devices are not synchronized to the heart's rhythm. Blood enters from the LV apex into the inflow cannula, transverses the pump, and then exits through the outflow cannula to the aorta. The pump is positioned either intra-abdominally or within a preperitoneal pocket in the left upper quadrant. The internal surface of the device contains a layer of pseudointima of titanium microspheres to reduce the thromboembolic risks. Continuous flow devices use axial or centrifugal pumps to generate continuous nonpulsatile blood flow [39]. They tend to have smaller size, less noise, and greater long-term mechanical reliability, compared with the pulsatile flow devices. It is important to understand the normal positioning of these devices and recognize potential complications.

Imaging of Normal LVADs

Evaluation for complications when clinically suspected is typically performed with echocardiography but often limited by the acoustic window and acoustic shadowing due to the metallic artifact from the device, as well as other postoperative changes such as mediastinal and pleural air, reduced mobility, or presence of drainages and dressings. CT provides noninvasive, high-resolution imaging of LVADs and is useful in identifying normal and pathologic appearances [40•]. Transesophageal echocardiography may provide a better assessment of RV function in such cases, but does not provide adequate visualization of the entire inflow and outflow cannulas due to limited depth of imaging and volume of coverage. Imaging of the upper ascending aorta is limited due to reverberation artifacts. CT has several potential advantages over echocardiography for LVAD imaging, including no limitation by acoustic window and better LVAD cannula visualization without acoustic shadowing [41]. In the normal position, the inflow cannula should direct into the LV cavity without obstruction or surrounding thrombus formation. The outflow cannula should attach to the ascending or descending thoracic aorta, (Fig. 5). Cine imaging with ECG gating of the heart in the short-axis and in multiple long-axis planes should be performed to assess cardiac motion and dynamic positioning of the inflow cannula. Neutral septum position, significant reduction in mitral regurgitation and a closed aortic valve during systole are indicators that the LVAD is functioning properly to unload the LV. A recent article has suggested that CT measurement of cardiac output has good correlation with measurements by Swan-Ganz thermodilution and can help with adjustment and potential weaning of LVAD support in patients [41].

Complications after LVAD Implantation

CT has been shown to be accurate in identifying critical findings in patients with LVADs, including thrombosis and inlet cannula malposition [42•]. Thrombus can be seen as low-attenuation material within the LV that is often adherent to the inflow cannula. CT may be helpful in providing hemodynamic assessment of LVAD output [42•]. The most common postoperative complications in these patients included RV dysfunction, cannula obstruction, pericardial hematoma, or pulmonary embolism. Hemodynamic instability during early postoperative state is most commonly due to low flow rates. Early complications include cannula obstruction, hypovolemia from hemorrhage and tamponade. A normally positioned cannula is directed into the LV without abutting any wall [43]. Obstruction can result from kinked inflow or outflow cannula, LV hypertrophy, small or collapsed LV or deviated septum due to severe RV failure. Right-sided failure can occur as an early or late complication, and is a major contributor in morbidity and mortality after LVAD implantation [39]. Accurate evaluation of RV function in patients with LVAD remains challenging [44]. Evaluation of RV dimensions and function by transthoracic echocardiography is technically difficult because of the intrinsic complex RV geometry and device-related artifacts [45]. ECG-gated cardiac CT allows RV dimensions and function evaluation with higher accuracy and reproducibility compared with echocardiography [46•].

Postoperative pericardial hemorrhagic effusions can be seen in CT as high-attenuation fluid symmetrically surrounding the heart. CT signs of tamponade include dilatation of the inferior vena cava, flattening of the heart border or severe compression of the RV or right atrium, and compression of the CS. Late complications include thrombus formation, aortic stenosis or insufficiency, and infection. The aortic valve remains closed during most of the cardiac cycle for normal LVAD functioning. Aortic fusion or some degree of stenosis occurs from the continuous closure, resultant stasis, and abnormal flow rates in up to 88 % of patients with LVADs [47]. Progressive aortic insufficiency may occur after LVAD implantation due to increased transaortic valvular gradient and constant back-pressure, and may decrease effective forward outflow from the device [48]. Retrospectively ECG-gated

CT can provide morphologic and dynamic information of the aortic and mitral valves throughout the cardiac cycle [49]. Infection is another common complication, and localized infection can be seen in CT as gas or fluid collections around the driveline or the pump itself. Three-dimensional reconstruction of the imaging data allows LVAD evaluation from different views [42•]. Improved spatial and temporal resolution, with retrospective gating allows for assessment of both LV and RV function. The combination of hemodynamic information and reliable anatomic information by CT is a powerful tool for noninvasive assessment of LVAD.

Conclusion

The presence of endocardial leads produces artifacts that may make the assessment of coronary arteries and cardiac function less reliable. The noninvasive cardiac vein mapping prior to the placement of a biventricular pacemaker is among the appropriate indications for cardiac CT. CT venography enables preprocedural assessment of the cardiac venous anatomy, which in turn allows the assessment of the potential feasibility and success of the procedure. The importance of CT, as a method of coronary venous system visualization, will probably continue to increase along with technical progress in the construction of new generations of CT scanners and post-processing algorithms. Myocardial scar assessment with CT is an alternative for patients with devices. Multimodality imaging that merges functional with anatomic information may facilitate such an individualized approach to tailor an LV lead implant strategy and proactively target a myocardial segment of interest. CT is also a useful tool to assess the normal functioning and potential complications of LVADs. Despite concern about effect of radiation on implantable cardiac devices, no clinical significant effect has been reported in patients with implanted devices undergoing diagnostic CT examinations.

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Fig. 1.
Metal artifacts from (A) the right atrial (RA) lead affecting the assessment of the right coronary artery (RCA), (B) the left ventricular (LV) lead on left circumflex artery (LCx), and (C) the right ventricular (RV) lead on the distal left anterior descending artery (LAD)

Fig. 2. Transaxial image (A) and 3D-volume rendered CT reconstruction (B) showing a chronic left ventricular lead perforation with the tip of the lead (arrow) extruding beyond the cardiac margin

Fig. 3. Volume rendered CT reconstruction of the coronary venous system (A) pre- and (B) post-CRT implant and corresponding invasive retrograde coronary venography (C, D). Three left marginal veins drain into the great cardiac vein (GCV) and are denoted by 1, 2, and 3 respectively. The left ventricular lead is placed in the first left marginal vein (B, D)

Fig. 4. Short-axis view of the mid LV (A) noncontrast, (B) contrast-enhanced first-pass perfusion, (C) delayed enhancement acquired 10 minutes after contrast administration in a patient with a pacemaker. Note the hypoperfusion and thinned myocardium of the anterior and anterolateral segments on contrast-enhanced scan (B) and the hyper-enhancement (arrows) in the delayed scan (C), which are consistent with myocardial scar

Fig. 5.

(A) Scout image of dual source CT images of HeartMate II where the continuous pump is positioned intra-abdominally (1), the inflow cannula (2) is attached to the left ventricular apex, and the outflow cannula (3) is attached to the ascending aorta. (B) Axial CT image shows (1) the inflow cannula attached to the left ventricular apex, (2) layer of pseudointima within the outflow cannula, and the interventricular septum in a neutral position (black arrows). (C) Sagittal CT images of outflow cannula of HeartMate II connected to the ascending aorta (Ao). (D) Postoperative hemorrhage and pericardial effusion after biventricular assist device implantation. Axial CT image shows a moderate circumferential hemorrhagic pericardial effusion (arrows)