

Three-Dimensional Imaging for Coronary Interventions

Techniques and technologies for more accurate vessel views.

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Traditional standard angiography of the coronaries is limited by its two-dimensional (2D) projection of complex three-dimensional (3D) structures and the consequent imaging artifacts (vessel overlap, vessel foreshortening, lesion eccentricity, etc) that could limit interpretation and analysis. Computed tomography angiography (CTA), magnetic resonance angiography (MRA), and angiography-based innovative real-time 3D reconstruction software are major advances in coronary imaging. These techniques provide 3D vessel imaging and enable the subsequent analysis of 3D properties with potential important clinical implications during coronary interventions.

Accurate evaluation of the anatomy and pathology of the coronary vasculature is the key goal of angiographic acquisitions. Imaging techniques are used to plan and execute treatment by allowing the recognition and quantification of a variety of vessel and lesion features. The increasing complexity of endovascular interventions has led to a need for more complete and accurate representation of the 3D geometry of target vessels and lesions.

Traditional standard, catheter-based angiography presents luminal information in the format of 2D projection images. It is now possible to convert these 2D images into a 3D format through modeling or reconstruction algorithms. This allows for better understanding of vessel characteristics such as curvature, bifurcation angles, and vessel conformational changes.

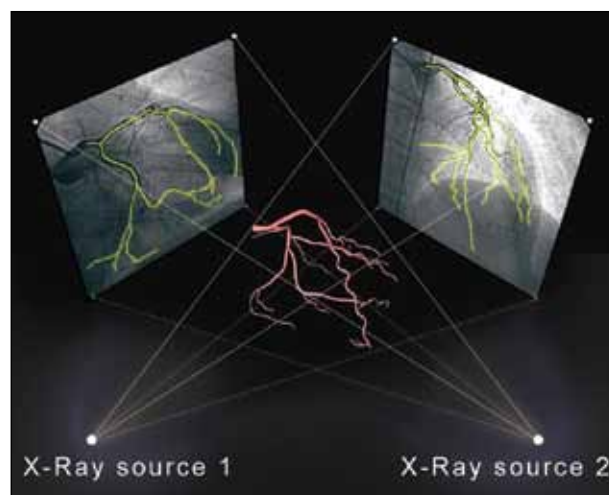


Figure 1. Image representation of the 3D modeling technique. Modeling uses two different orthogonal angiographic sources for the creation of a centerline and cross-sectional area. Adapted with permission from Mukherjee D, Bates E, Roffi M, et al. *Cardiovascular catheterization and intervention: a textbook of coronary, peripheral, and structural heart disease*. 1st ed. New York, NY: Informa Healthcare; 2010:209.

TECHNIQUES THAT ALLOW 3D DATA IMAGE PROCESSING

Two techniques have been developed for the 3D representation of vascular structures. The 3D modeling technique uses two or more angiographic projections to

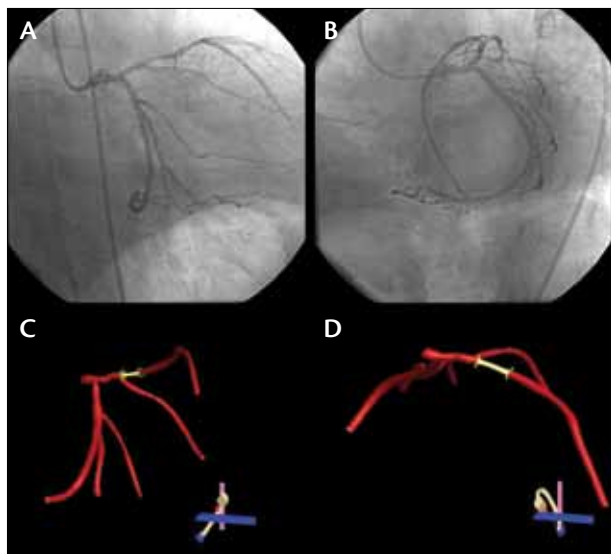


Figure 2. 3D modeling analysis of a mid-left anterior descending artery lesion. Initial right anterior oblique (RAO) caudal (A) and left anterior oblique caudal (B) projections > 30° in angulation utilized for 3D coronary model reconstruction. 3D model in operator-selected view of RAO 1/caudal 39 projection with 17% foreshortening as described on the optimal-view map (OVM) (C). Rotated 3D reconstruction to RAO 45/cranial 30 minimizing the foreshortening to 0% while enabling visualization of the first diagonal branch (D).

extract features of the vessel and create a 3D representation (Figure 1). This technique uses 3D centerline data and shaded or rendered surfaces; the diameter and 3D morphologic structure of the vessel are subsequently derived with a computer algorithm.¹ In contrast, the 3D reconstruction technique refers to a computer-generated representation of the true shape and size of the imaged vessel using actual volumetric data obtained from rotational angiography, CTA, or MRA. This technique depends on multiple image projections for the creation of a volumetric representation of the vessel and is more advanced than vessel modeling.

3D Modeling

A 3D modeling algorithm using single-plane angiography that does not require a calibration object has been developed and prospectively validated.²⁻⁶ The accuracy of the 3D modeling method depends on a computer-based, four-step algorithm that integrates 2D projections into a 3D image.⁷⁻¹⁰

Modeling only requires orthogonal views of a given structure. Given the lack of volumetric data, it is not as precise as reconstruction, but it allows 3D imaging of traditionally difficult-to-reconstruct structures, such as

the moving coronary tree. This is particularly important in standard angiography laboratories without rotational angiography capabilities.

These modeling algorithms have been utilized and previously described and validated in coronary arteries. The 3D protocol involves the semiautomatic extraction of the arterial contour (centerline and diameter) from the 2D digital angiogram. Branch vessels are used as unique landmarks to calculate a transformation matrix that defines the relative location and orientation of the two projections of the 2D angiograms.² The 2D vessel features and the calculated transformation allow for the vessel skeleton, consisting of the 3D centerline and cross-sectional diameters, to be obtained (Figures 1 and 2).

3D Reconstruction

3D reconstruction images can be generated from imaging modalities that acquire volumetric data, such as rotational angiography (non-y-axis breaking technique), CT, or MRI.¹¹ Several methods that are capable of generating 3D images have been described; in general, these can be divided into surface-rendering or volume-rendering techniques.

The surface-rendering method relies on a computer algorithm to reconstruct intensity values that are above a defined threshold and represent volumetric surfaces within the dataset; all values below the set threshold are discarded and not used for image generation.¹² The resultant image is a representation of the surface contour, which appears 3D through computer-generated shading. Surface rendering, although fast, is less reliable for structures smaller than 2 to 3 mm because it uses only a small portion of the acquired data.¹²

The maximum-intensity projection algorithm is another commonly used surface-rendering technique.¹³ 3D imaging using volume rendering is a more powerful technique that incorporates the entire dataset into the 3D image. In contrast to surface-rendering techniques, intravascular details and spatial relationships between adjacent structures are preserved (Figure 3).

SELECTIVE ANGIOGRAPHY, CTA, AND MRA FOR 3D IMAGE ACQUISITION

Selective Angiography

Traditionally, invasive coronary angiography provides a 2D representation of a patient's coronary anatomy. There are well-known limitations of this technique involving vessel foreshortening, the most common being overlap and unappreciated tortuosity.¹⁴⁻¹⁷ Despite the acquisition of multiple angiographic views in an effort to overcome these limitations, quantitative measurements of vessel properties, such as length, diameter,



Figure 3. Volumetric reconstruction of a left coronary artery (A). The screen shot demonstrates the process for determining a vessel measurement using the 3D workstation (B).

and orientation, remain limited by foreshortening of the vessel segments and by unknown magnification factors.¹⁸ Additionally, despite the use of automated vessel detection tools and calibrated quantitative coronary angiography on 2D images, significant inaccuracies in the assessment of percent lesion stenosis remain, due to the frequent eccentric nature of coronary artery stenoses.¹⁸

Rotational angiography is a novel image acquisition technique in which the gantry is automatically rotated around the patient in a standardized trajectory in order to obtain multiple projection images.¹⁹ The justification for rotational acquisition is straightforward: in 2D x-ray projection images, coronary arteries and other vascular structures must be visualized from multiple projection angles to adequately appreciate their structure. The resultant panoramic view provides a 3D-like mental image of key anatomic features for diagnostic and interventional purposes.

Despite the large increase in the diversity of views of the arterial tree, some of the inherent limitations of 2D projection imaging remain. Rotational angiography cannot simulate views outside of the range of acquired images. It requires visual skills in the selection of optimal projections and provides no quantification of important 3D vessel features. Recognition of these limitations has resulted in the development of 3D imaging techniques using algorithms that utilize the raw angiographic data.

The generation of 3D vascular models makes use of the knowledge of 2D projected centerlines and diameters in at least two projections. In recent years, several variants of these techniques were introduced to generate a 3D model of the coronary artery tree.^{12,13} These techniques all use two or more projection images, either acquired sequentially on a monoplaner^{2,20,21} or simultaneously on a biplane^{20,22} vascular C-arm system. The accuracy of vessel length, diameter, and bifurcation angle

determination using 3D reconstruction or modeling techniques has already been demonstrated in several studies.^{2,23}

Commercial x-ray systems with rotational angiography capabilities are currently available with 3D reconstruction software for nonmoving vascular trees. Development of these reconstructions is ongoing for dual-motion rotational angiography.

The reconstruction technique is different from

the modeling technique in that all images from the rotational acquisition are used, and the reconstruction process is completely automated based on algorithms used in CT imaging (ie, volumetric-based 3D reconstruction).

These algorithms cannot be applied for the coronary arterial tree because the coronary tree moves and changes shape. New algorithms that are either retrospectively gated or provide motion compensation solutions are under development, and some have been validated (Figure 3). These approaches, if successful, will allow the completely automated reconstruction of the moving coronary artery tree immediately after the acquisition of a rotational angiogram with an arc of 180°. A recent publication from our group on the clinical feasibility of a fully automated 3D reconstruction of rotational coronary x-ray angiography validates this hypothesis.²⁴

Coronary CT Angiography

Advances in multidetector computed tomography (MDCT) have provided the opportunity to noninvasively and three-dimensionally evaluate the coronary vasculature in a safe and efficient manner. Newer CT imaging technology with faster gantry rotations, dual x-ray source scanners, multidetector 64-row acquisitions, and electrocardiogram gating has substantially improved both temporal and spatial resolutions to adequately visualize the moving coronary vasculature. Current-generation MDCT scanners are able to achieve a spatial resolution of 0.4 mm with a temporal resolution as low as 83 milliseconds during cardiac acquisition of < 15 seconds. Initial, relatively small studies evaluating the diagnostic accuracy of 64-slice MDCT compared with diagnostic cardiac catheterization have demonstrated sensitivities ranging from 80% to 94% and specificities ranging from 95% to 97%.²⁵⁻²⁷

TABLE 1. PROPOSED ADVANCED APPLICATIONS UTILIZING 3D VASCULAR IMAGING

Application	Clinical Uses and Benefits
Computation of optimal views	Optimize diagnostic image acquisition using data from another imaging modality
	Optimize working fluoroscopic views for interventional therapy
	Reduce radiation dose and contrast volume
Selection of interventional equipment	Match patient-specific analysis of 3D vessel features with equipment attributes of size, shape, and performance
	Reduce costs and other pitfalls of current empirical approach
Simulation of cardiovascular procedures	Training and performance assessment of CV procedures
	Patient-specific practice before intervention
	Improve efficiency of training and reduce hazards of patient exposure to operator's early learning curve
Database creation	Catalogue and statistically analyze clinically important anatomical properties
Clinical decision support systems	Operator support by putting patient-specific attributes in context of a database including interventional outcomes
Navigation systems	Improve interventional outcomes, especially in complex cases requiring hand-eye tasks at or above the upper threshold of traditional catheter manipulation skills
	Reduce radiation dose during fluoroscopically guided procedures
Multimodality fusion	Improve patient selection and interventional outcomes by improving localization of functional and anatomical abnormalities
Cardiovascular device design and testing	Provide a spectrum of human vascular features to enhance matching of device design to target
	Analyze relationship of 3D vascular features to device failures

Routine evaluation of coronary MDCT involves segmentation of the individual visualized coronary vessels. From the resulting coronary tree, determinations are easily made regarding vessel length, curvature, branching angles, and stenosis length, location, and severity (Figure 4). Additionally, atherosclerotic plaque composition can be easily assessed; due to high CT attenuation of calcified lesions, they are differentiated from fibrous or lipid-rich lesions. These angiographic features are easily displayed on MDCT-derived 3D volumetric and anatomic representations.^{28,29}

Magnetic Resonance Coronary Angiography

Cardiac MRI is a rapidly evolving noninvasive imaging modality that will further advance the goal of providing 3D vascular imaging. Cardiac MRI has become an established imaging modality for the assessment of various cardiac disorders, including myocardial viability, infiltrative cardiomyopathies, congenital heart disease, anomalous

coronary arteries, cardiac masses, and aortic and pericardial diseases.

Magnetic resonance coronary angiography (MRCA) is a technique that allows the noninvasive visualization of coronary arteries. Since it was first reported in 1987,³⁰ MRCA has gained considerable importance as a noninvasive method to diagnose coronary artery stenoses and is an area of active research. MRCA is beneficial for not only visualization of the coronary arteries but also for the evaluation of cardiac morphology and function in one sitting. The challenges for MRCA include compensation for cardiac and respiratory motion, spatial resolution and coverage, and signal-to-noise limitations.

ADVANCED APPLICATIONS BASED ON 3D VASCULAR DATA

3D vascular trees enable a variety of advanced applications that extend their clinical utility into multiple emerging technologies (Table 1).

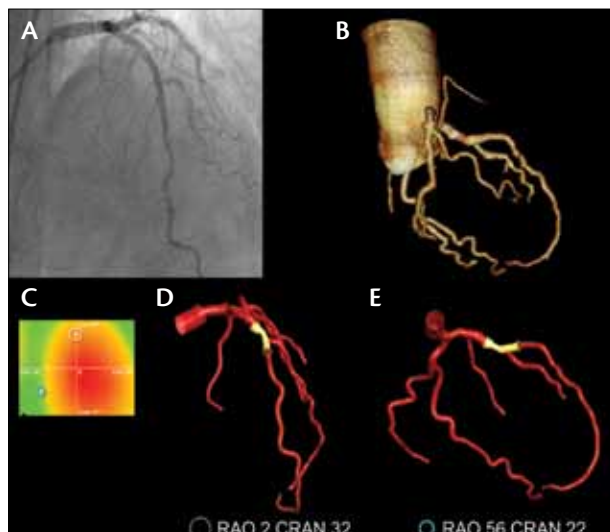


Figure 4. Representation of extracted CT data and angiogram. Angiogram with a distal left anterior descending lesion (A), the extracted CTA data (B), OVM based on CTA data (C), proposed nonforeshortened and nonoverlapped views based on OVM for the lesion segment (D, E).

Optimal Views and Global Optimal-View Maps

3D vascular trees generated with CTA, MRA, or traditional x-ray can be used to simulate all possible angiographic views of the vascular tree. These 3D datasets can be used to simulate 2D images in a similar format to those currently employed for guidance of endovascular interventions, such as fluoroscopy and ultrasound. With the expanded use of CTA and MRA, it will be increasingly important to maximize the use of the information from the diagnostic modality when the patient comes to interventional therapy.

The clinical value of using a 3D vascular tree to simulate angiographic views is to enhance patient safety and potentially improve interventional outcomes. Computer selection of an optimal view can be done before the intervention as part of the preprocedure planning process (Figure 4). For the interventional procedure, the traditional trial-and-error method of finding good angiographic views is often costly in expending time, radiation, and contrast. Optimizing working views for interventions should reduce visualization-related mistakes and prevent complications.

The placement of the gantry in a location to produce useful angiographic information is a fundamental task in both diagnostic imaging and the performance of endovascular interventions. Obtaining optimal angiographic views is critical to assessing lesion morphology, extent of disease, and involvement of major branch segments. These considerations have become more prominent since the

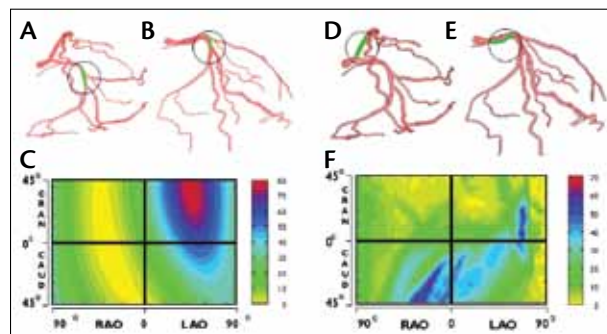


Figure 5. OVM example in relation to a midcircumflex lesion (A, B) and a proximal left anterior descending lesion (D, E). Notice the OVM for the midcircumflex segment (C) as it relates to overlap. The same is shown as an OVM for the proximal left anterior descending lesion (F). Reprinted with permission from HMP Communications. From Garcia JA, Eng MH, Wink O, et al. Image guidance of percutaneous coronary and structural heart disease interventions using a computed tomography and fluoroscopy integration. *Vascular Disease Management*. 2007;3:49-57.

advent of interventional cardiology, as the objective has become significantly more demanding than simply noting the quality of distal conduits for bypass surgery.

Three-dimensional vascular trees registered or aligned in the coordinate system of gantry location can be used to solve the imaging tasks commonly encountered. First, overlap of vessels in the tree needs to be minimized. Second, segments of the tree need to be imaged with the imaging system perpendicular to the axis of the vessel segment such that no foreshortening is produced in the resultant projection image. Experienced interventionists do not always choose views that minimize foreshortening of the diseased segment.

Several methods can be used to produce useful images that avoid overlap and minimize foreshortening for all segments of interest in the vascular tree. Computer graphics can be used to display the tree in a variety of views, and the operator can select appropriate views (Figures 2 and 4). Alternatively, algorithms can be written to automatically process the data, recommend specific views, or produce visual guides that incorporate a parameter, such as the extent of foreshortening for a vessel segment of interest for all angiographic views^{31,32} (Figure 5).

Selection of Interventional Equipment Based on 3D Information

By providing an accurate assessment of coronary lesion length and reference vessel diameter, 3D datasets of the coronary anatomy allow objective decisions regarding the length and diameter of balloons and stents used to

treat obstructive disease.¹⁸ The accuracy of these assessments should reduce the incidence of events such as oversizing of balloons, over- and undersizing of stents, and inadequate lesion coverage by drug-eluting stents resulting in placement of additional stents. These events are clinically relevant, affecting the safety, efficacy, and cost of interventional procedures.

Together with comprehensive lesion assessment, the ability of 3D datasets to make clear the orientation of coronary artery ostia and to measure vessel tortuosity and calcification should greatly facilitate the choice of guide and guidewire for a given intervention. At present, the synthesis of these data elements results in educated judgments regarding the particular guide shape and caliber required to provide support to deliver interventional equipment and the specific type of wire that will best negotiate a lesion and provide sufficient support for device delivery. Hopefully, by accumulating large datasets of baseline 3D assessments and recording the success of various guides and guidewires in subsequent interventions, a degree of scientific objectivity may be applied to these decisions.³²

CONCLUSIONS

The advantages of 3D over traditional 2D projection images are multiple. The fundamental fact is that the object of interest, the coronary tree, is 3D, and diagnosis and treatment are tightly linked to understanding and accurately quantifying patient-specific vascular properties. Moving from 2D to 3D vascular images now requires the standardization of terminology and the development of new analytic and interventional treatment guidance tools. Finally, 3D vascular imaging enables a variety of other advanced applications that should have a profound impact on patient safety, clinical outcomes, and the training and performance of interventionists. Further clinical studies are required to evaluate the impact of these techniques on acute procedural success and outcomes. In the meantime, these techniques are available and provide the ability to preplan and facilitate procedures. ■

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- Klein JL, Hoff JG, Peifer JW, et al. A quantitative evaluation of the three dimensional reconstruction of patients' coronary arteries. *Int J Card Imaging*. 1998;14:75-87.
- Chen SJ, Carroll JD. 3D reconstruction of coronary arterial tree to optimize angiographic visualization. *IEEE Trans Med Imaging*. 2000;19:318-336.
- Chen SY, Carroll JD, Messenger JC. Quantitative analysis of reconstructed 3D coronary arterial tree and intracoronary devices. *IEEE Trans Med Imaging*. 2002;21:724-740.
- Hoffmann KR, Metz CE, Chen Y. Determination of 3D imaging geometry and object configurations from two biplane views: an enhancement of the Metz-Fencil technique. *Med Phys*. 1995;22:1219-1227.
- Messenger JC, Chen SY, Carroll JD, et al. 3D coronary reconstruction from routine single-plane coronary angiograms: clinical validation and quantitative analysis of the right coronary artery in 100 patients. *Int J Card Imaging*. 2000;16:413-427.
- Metz CE, Fencil LE. Determination of three-dimensional structure in biplane radiography without prior knowledge of the relationship between the two views: theory. *Med Phys*. 1989;16:45-51.
- Delaere D, Smets C, Suetens P, Marchal G, Van de Werf F. Knowledge-based system for the three-dimensional reconstruction of blood vessels from two angiographic projections. *Med Biol Eng Comput*. 1991;29:NS27-36.
- Ding Z, Friedman MH. Quantification of 3D coronary arterial motion using clinical biplane cineangiograms. *Int J Card Imaging*. 2000;16:331-346.
- Godbout B, de Guise JA, Soulez G, Cloutier G. 3D elastic registration of vessel structures from IVUS data on biplane angiography. *Acad Radiol*. 2005;12:10-16.
- Slager CJ, Wentzel JJ, Schuurbers JC, et al. True 3-dimensional reconstruction of coronary arteries in patients by fusion of angiography and IVUS (ANGUS) and its quantitative validation. *Circulation*. 2000;102:511-516.
- Rasche V, Buecker A, Grass M, et al. ECG-gated 3D-rotational coronary angiography (3D RCA). Paris: Springer, 2002.
- van Ooijen PM, van Geuns RJ, Rensing BJ, et al. Noninvasive coronary imaging using electron beam CT: surface rendering versus volume rendering. *AJR Am J Roentgenol*. 2003;180:223-226.
- Mallouhi A, Bonatti H, Peer S, et al. Detection and characterization of perianal inflammatory disease: accuracy of transperineal combined gray scale and color Doppler sonography. *J Ultrasound Med*. 2004;23:19-27.
- Galbraith JE, Murphy ML, de Soya N. Coronary angiogram interpretation. Interobserver variability. *JAMA*. 1978;240:2053-6.
- Scanlon PJ, Faxon DP, Audet AM, et al. ACC/AHA guidelines for coronary angiography. A report of the American College of Cardiology/American Heart Association Task Force on practice guidelines (Committee on Coronary Angiography). Developed in collaboration with the Society for Cardiac Angiography and Interventions. *J Am Coll Cardiol*. 1999;33:1756-1824.
- Spears JR, Sandoz T, Baim DS, Paulin S. The minimum error in estimating coronary luminal cross-sectional area from cineangiographic diameter measurements. *Cathet Cardiovasc Diagn*. 1983;9:119-128.
- Topol EJ, Nissen SE. Our preoccupation with coronary luminology. The dissociation between clinical and angiographic findings in ischemic heart disease. *Circulation*. 1995;92:2333-2342.
- Green NE, Chen SY, Hansgen AR, Messenger JC, Groves BM, Carroll JD. Angiographic views used for percutaneous coronary interventions: a three-dimensional analysis of physician-determined vs. computer-generated views. *Catheter Cardiovasc Interv*. 2005;64:451-459.
- Maddux JT, Wink O, Messenger JC, et al. Randomized study of the safety and clinical utility of rotational angiography versus standard angiography in the diagnosis of coronary artery disease. *Catheter Cardiovasc Interv*. 2004;62:167-174.
- Chen SJ, Hoffmann KR, Carroll JD. Three-dimensional reconstruction of coronary arterial tree based on biplane angiograms. *SPIE Med Imag*. 1996;2710:103-115.
- Shechter G, Devernay F, Coste-Maniere E, Quyyumi A, McVeigh ER. Three-dimensional motion tracking of coronary arteries in biplane cineangiograms. *IEEE Trans Med Imag*. 2003;22:493-503.
- Nguyen TV, Sklansky J. Computing the skeleton of coronary arteries in cineangiograms. *Comput Biomed Res*. 1986;19:428-444.
- Chen SY, Metz CE. Improved determination of biplane imaging geometry from two projection images and its application to three-dimensional reconstruction of coronary arterial trees. *Med Phys*. 1997;24:633-654.
- Neubauer AM, Garcia JA, Messenger JM, et al. Clinical feasibility of a fully automated 3D reconstruction of rotational coronary X-ray angiograms. *Circ Cardiovasc Interv*. 2010;300:71-79.
- Leber AW, Knez A, von Ziegler F, et al. Quantification of obstructive and nonobstructive coronary lesions by 64-slice computed tomography: a comparative study with quantitative coronary angiography and intravascular ultrasound. *J Am Coll Cardiol*. 2005;46:147-154.
- Leschka S, Alkadhi H, Plass A, et al. Accuracy of MSCT coronary angiography with 64-slice technology: first experience. *Eur Heart J*. 2005;26:1482-1487.
- Raff GL, Gallagher MJ, O'Neill WW, Goldstein JA. Diagnostic accuracy of noninvasive coronary angiography using 64-slice spiral computed tomography. *J Am Coll Cardiol*. 2005;46:552-557.
- Budoff MJ, Oudiz RJ, Zalace CP, et al. Intravenous three-dimensional coronary angiography using contrast enhanced electron beam computed tomography. *Am J Cardiol*. 1999;83:840-845.
- Nieman K, van Geuns RJ, Wielopolski P, Pattynama PM, de Feyter PJ. Noninvasive coronary imaging in the new millennium: a comparison of computed tomography and magnetic resonance techniques. *Rev Cardiovasc Med*. 2002;3:77-84.
- Paulin S, von Schulthess GK, Fossel E, Krayenbuehl HP. MR imaging of the aortic root and proximal coronary arteries. *AJR Am J Roentgenol*. 1987;148:665-670.
- Garcia JA, Movassaghi B, Casserly IP, et al. Determination of optimal viewing regions for X-ray coronary angiography based on a quantitative analysis of 3D reconstructed models. *Int J Cardiovasc Imaging*. 2009;25:455-462.
- Garcia JA, Movassaghi B. Computer assistance for solving imaging problems. *Cardiol Clin*. 2009;27:503-512.