Three-Dimensional Coronary Angiography

The justification, technology, applications, and barriers to three-dimensional coronary imaging.

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Coronary angiography is changing in several fundamental ways. The ability to visualize the human coronary arteries in a three-dimensional (3D) format, a central new functionality, will soon be a reality in routine patient care. The traditional two-dimensional (2D) projection image that is ubiquitous in clinical practice will not disappear; rather image processing to render coronary arteries in 3D and advanced analysis tools will complement the images of conventional angiography. This article will examine the clinical reasons that advances in coronary angiography are needed, discuss some of the central technical themes, and provide an overview of what is now available and what is coming to the clinical arena soon. Finally, change is not immediate, and the barriers to profound changes in this field due to advancements in technology will be discussed.

During the last few decades, progress has occurred in catheter-based coronary angiography including the transition to standardized digital format and the replacement of image intensifiers with flat detectors. These changes have enabled the next major transition, which primarily involves the processing of these digital files into more realistic image representations, unique quantitative analysis, and decision-assistance tools. These advancements will allow the interventionist to understand anatomy better, quantify key features needed for percutaneous coronary intervention (PCI), and work more efficiently. The transition to 3D is a major part of this next evolution in coronary angiography, as has been the transition of 3D in other modalities, such as computed tomography (CT) angiography, magnetic resonance angiography, and ultrasound.

Cardiologists are becoming used to viewing the coronary tree in a 3D format that is routinely available with CT angiography. They have a new appreciation of the curvilinear nature of the coronaries, the complexities of lesions, and the unusual nature of x-ray projection images that flatten the 3D shape.

Figure 1. This is an example of a coronary 3D model created from two angiographic images. Not shown here are the other models created over the entire cardiac cycle. An analysis of changes in coronary shape during underlying heart motion has been done. The areas noted in blue and green indicate regions in this right coronary artery where curvature increases and decreases during the cardiac cycle. These are also called flexion points.
The imaging skills of an experienced interventionist are central to the performance of accurate diagnostic studies and in guiding the intervention by efficiently and competently using the major modality of x-ray imaging. These skills are being further put to the test with the movement of PCI into more complex subsets of coronary artery disease. PCI is a mature therapeutic technique; many interventionists have years of experience in using traditional angiography, and the vast majority of interventions are successful and uncomplicated. Are there really any significant remaining weaknesses in PCI related to 2D projection images that justify improving the technology of imaging with 3D?

WHY 3D?

Inherent limitations in traditional angiography that play out in specific ways in the world of PCI involving coronary stenting are summarized in Tables 1 and 2. If the coronary arterial tree could be presented to the interventionist in its true 3D shape and if there were quantitative tools to extract key 3D features, then coronary imaging, PCI planning, and PCI execution could potentially be improved in multiple ways. Furthermore, the techniques of image acquisition with traditional angiography are not standardized, but are subjectively chosen and highly dependent on the 3D visual skills of individual operators working in the bizarre, 2D, shadow-image format of projection.

Technological advancements should address clinical problems that interventional cardiologists agree are still present today. Reduction of radiation is an overriding patient safety issue and is also relevant to those who perform the procedure. Contrast volume directly impacts the occurrence of contrast nephropathy, volume overload, and the need to stage complex PCI. Prolonged and complex PCI procedures also have a different complication profile. Enhancing workflow and task completion have implications on the safety and efficiency of the procedure room; we acknowledge that 5% to 10% of PCIs are especially long and difficult. Other potential benefits of technology advancement involve providing the operator with greater confidence in decision making and task performance before, during, and after PCI. Because the transition to 3D is central to technological advancement, the next issue to be addressed is how a 3D coronary image can be produced.

HOW TO PRODUCE 3D IMAGES

Projection images can be transformed into 3D models and volumetric 3D reconstructions in a matter of minutes. The modeling approach and the reconstruction technique have many differences and will be described separately.

Coronary Modeling

The 3D modeling technique has been under development for several decades and, in the last decade, modeling has been introduced in the form of several products. Our colleague, James Chen, PhD, has been the pioneer in this field. Most approaches use two or more angiographic projections (Figure 1). The second step is called image segmentation and involves the extraction of the centerline and diameters of all vessels to be included in the model. Next, the transformation-defining relative location and orientation of the two views is calculated. From this transformation, the skeleton of the coronary arterial tree is created and computer graphics are used to display the tree as a 3D representation. The model can be manipulated (ie, rotated), allowing viewing that simulates
any gantry position. There are three major commercially available systems that perform coronary modeling: the CardiOp-B package (Paieon Medical, Rosh Ha'ayin, Israel); the 3D-CA package (Philips Medical Systems, Bothell, WA); and the Cardiovascular Angiography Analysis System for 3D Quantitative Coronary Analysis (Pie Medical Imaging, Maastricht, The Netherlands). Dr. Chen’s system has the most advanced quantitative tools but is not commercially available; it is being used internally in projects to better quantify 3D and four-dimensional vascular properties in many locations (arterial and venous) and the effect of implantable devices.

Coronary Reconstruction

The reconstruction technique is a newer approach that has not yet been commercially released for coronary applications. Reconstruction is in many ways a more advanced technology that has multiple advantages over the current modeling techniques, one being that it is completely automatic without the need for user interaction to produce a model. Three-dimensional volumetric datasets are typically generated not from traditional fixed views but from rotational angiography. These 180° or greater arcs of angiographic projection images are automatically processed for the creation of a volumetric representation of the vascular tree. The algorithm for performing this reconstruction has been improved with reduced noise and artifacts as shown in Figure 2. The resulting CT-like datasets can be rendered on the screen in various ways. Volume rendering is one visualization technique to display the entire 3D dataset. Other techniques can be applied, such as surface renderings, maximum intensity projections, and planar reformatting, which allow inspection of the data much as in CT angiography. Similar to a model, the reconstructed arterial tree can be free-rotated to simulate any vantage point.

Once the interventionist has either a 3D model or a reconstruction, how can it be used for clinical tasks? The initial examination of the 3D model or reconstruction by turning it on a computer screen allows an enhanced appreciation of 3D geometry. However, can there be clinically important functions and features extracted and quantified from the data or is it just a nice image with no practical value?

Computer Assistance for the Operator: The Coronary Optimal View Map

Three-dimensional modeling and 3D reconstructions can provide the datasets that allow development of an optimal

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**TABLE 1. GENERAL IMAGING-RELATED LIMITATIONS OF CATHETER-BASED CORONARY ANGIOGRAPHY**

- Ionizing radiation: Substantial radiation given with both diagnostic and PCI especially with prolonged and difficult procedures. Techniques and technologies to reduce radiation have a high priority.
- Contrast media: Renal toxicity, especially with pre-existent renal impairment, remains a major and frequent complication demanding efforts to limit volume.
- Technique of acquisition: Operator dependency on quality of study via selection of a variable number of fixed projection views to avoid vessel overlap and minimize lesion foreshortening.
- Image format: 2D projection images with inherent problems of foreshortening, overlap, and misrepresentation of key anatomical features, such as lesion length, bifurcation angles, and tortuosity.
- Angiographic visualization: Visualization of lumen leads to underestimation of disease and poor understanding of vessel wall.
- Interpretation and analysis: The subjective nature and semi-quantitative analysis using only those views acquired may lead to errors, especially during earlier years of experience.

**TABLE 2. SPECIFIC LIMITATIONS OF TRADITIONAL CORONARY ANGIOGRAPHY RELEVANT TO CORONARY STENTING**

- Failure to reach the lesion due to underestimation of factors determining resistance for delivery system advancement, such as the degree of proximal vessel tortuosity.
- Over-reliance on the trial and error system rather than advanced analysis predicting delivery success versus failure.
- Geographic miss is common in stent placement due to use of views producing suboptimal 2D projection images.
- Undersizing and oversizing of stent lengths and diameters based on “eyeball” estimates from suboptimal 2D images.
- Limited conformability of stents placed in underappreciated curved segments leading to vessel straightening and edge kinks.
- Limited assessment of stent expansion and wall apposition due, in part, to poor visibility of stents with thinner struts and larger patients.
- Inability to visualize all but the most gross examples of stent fracture.
view map. The map has gantry space as the coordinates in the right anterior oblique/left anterior oblique and cranial/caudal axes. This optimal view map can be generated for each coronary segment and provides foreshortening and overlap quantification for all segments for all gantry positions. Color coding is used to make it easy to find regions where a gantry position would be optimal to minimize foreshortening of the segment and avoid overlap with other vessels (Figure 3).

3D Quantitative Coronary Angiography

Quantifying 3D vessel properties and characteristics of a given vessel is increasing in contemporary interventional cardiology, as shown by the development of the SYNTAX score for selection of appropriate candidates for PCI with left main and multivessel disease. The American College of Cardiology and the American Heart Association outline the specific vessel properties that define the procedure outcome risk of a given lesion. It is important to note that these vessel characteristics are inherently 3D in nature, therefore, a complete analysis requires a 3D evaluation. Quantifications of 3D vessel geometric features, motion dynamics, and deformation analysis are now possible with 3D coronary images (Figure 1).

BARRIERS TO 3D

These changes in x-ray coronary angiography represent a major culture change for the interventional cardiologist, and thus, implementation will not happen overnight. The barriers to rapid and widespread adoption of these technologies are multiple, as outlined in Table 3. New angiographic systems are needed, and the capital costs are significant. Validation and proof of clinical value, with improvement in patient outcomes, are also needed; a few reports have been published. Unlike implanted device regulation, imaging devices are approved without demonstration of improved clinical outcomes. Finally, education and training may be minimal in using some new technologies, such as flat detectors, but 3D imaging involves new modes of image acquisition, processing, and, most importantly, a new way of using images.

CONCLUSION

Three-dimensional coronary imaging is emerging from the research lab into the clinical arena, driven by the acknowledgment of the limitations of traditional 2D techniques, enabled by many aspects of the digital processing revolution, and accelerated by the clinical challenges of more complex anatomical subsets undergoing PCI. As already demonstrated with rotational angiographic acquisition, 3D coronary imaging should further improve patient outcomes, starting with reduction of x-ray dose.
and contrast volume, but also including reducing mistakes and errors caused by suboptimal imaging skills and technology.

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