Multidetector-row computed tomography imaging of prosthetic heart valves: clinical and experimental aspects
Symersky, P.

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SUMMARY

BACKGROUND

Until recently, the CT imaging of PHV was thought to be of no additional value for the evaluation of PHV function. As moving metal objects, PHV appeared as streaks on CT images which were marred by artifacts and CT images yielded no additional information. Due to the rapid evolution of CT technology and marked improvements in temporal and spatial resolution, CT can provide a detailed picture of the periprosthetic anatomy. In selected patients, CT imaging may contribute to medical decision making in patients with suspected prosthetic valve dysfunction. The limitations and possibilities of CT imaging are illustrated in chapters 2 and 3. As one of the first series reporting CT imaging for PHVs, chapter 2 demonstrated clear pathology found with CT in the majority of patients suspected of prosthetic valve obstruction. Using standard retrospectively ECG-gated acquisition protocols based on coronary CT angiography, various modes of obstruction could be identified. This included pannus (subprosthetic tissue proliferation), protrusion of a mitral prosthesis in the LVOT, incomplete closure of a single leaflet of a bileaflet valve, and an abnormal orientation of a valve in relation to the LVOT axis. Conversely, the lack of abnormalities favored the diagnosis of patient prosthesis mismatch. The patient presented in chapter 3 further illustrates the potential of CT for the evaluation of PHV obstruction. Although these results were promising, various downsides to CT imaging of PHV were evident. For example, the metal alloys of some mechanical PHV caused considerable artifacts. In addition, the image quality varied considerably during the cardiac cycle and the radiation dose associated with CT would limit the use of CT to all but highly selected patients. Hence, in the following chapters we sought to elucidate the various determinants of CT image quality of PHV. We approached the problem of optimizing image quality by 1) assessing the compatibility of various PHV with CT imaging, 2) developing a model for the comparison of CT images of PHV, 3) modulate various CT acquisition and image reconstruction protocols to optimize image quality and 4) using a robust test to assess image quality of PHV to evaluate the effect of motion and various acquisition protocols on image quality.

FEASIBILITY

In a first step to study the feasibility of CT imaging of PHV, a general survey of CT image quality of PHV in the common CT database of the Academic Medical Center and University Medical Center in Utrecht of ECG-gated cardiac scans was performed (chapter 4). Eighty-four ECG-gated CT data of 83 patients were found with 91 PHVs. The study found that except for PHV made of cobalt chrome alloys (i.e. Bjork Shiley, Sorin tilting disc), the image quality for commonly used mechanical and biological PHV was good enough to allow imaging of the periprosthetic and prosthetic structures with a variable amount of artifacts. Although these results showed that CT imaging of most PHV is feasible, the goal of the study was not to identify pathology. Considerable
variations in artifacts and image quality still posed a challenge to provide a constant and reproducible diagnostic image quality which is needed for widespread use of CT.

DEVELOPMENT OF A MODEL

In order to exactly study the influence to PHV components and leaflet motion, an in vitro model was developed. This model, which is described in chapter 5, allows the controlled comparison of CT images of PHV under standardized pulsatile conditions. With this model several important observations could be made by retrospectively ECG-gated image acquisition of five valves: Björk-Shiley Monostrut, Medtronic-Hall, St Jude Masters, Carbomedics, and ON-X. The principal findings were: 1) the in vitro model can serve as a platform to establish and compare MDCT imaging characteristics of various valves; 2) image quality of PHV made of a cobalt chrome alloy is marred by severe artifacts which precludes the detection of strut fractures of Björk-Shiley convexo-concave valves; 3) currently implanted PHV are associated with good in vitro MDCT image quality, and, surprisingly, 4) the image quality of the periprosthetic structures was good to excellent in the modern PHV and markedly superior to in vivo image quality. Despite these encouraging results, 20% of the leaflet images displayed angulations which probably were related the limited temporal resolution of the CT.

In chapter 6, the radiopaque anatomy of the PHV was analyzed in order to establish a method to quantify artifacts generated by PHV. Because PHV-related artifacts appeared as one one of the most important determinants of image quality, a method of quantifying artifacts would allow comparison between valves and comparison between specific acquisition and image reconstruction protocols. To quantify artifacts, the CT densities (in Hounsfield Units) were measured of the prosthetic ring and leaflets of the ON-X, Carbomedics, St Jude and Medtronic Hall valve. Differences in CT densities of the prosthetic ring were ascribed to the different alloys used (e.g. nickel alloy for the St Jude valve and titanium for the Medtronic Hall valve). Differences in the CT density of the leaflets were ascribed to the amount of tungsten used to impregnate the carbon structure of the leaflets.

For the quantification of artifacts, thresholds for hypodense (<-50 HU) and hyperdense artifacts (>200 HU) were chosen in relation to CT density of the surrounding structures (i.e. PMMA and water). Because the hyperdense artifacts included the radiopaque structure of the PHV, thresholds of 800 HU (for the leaflets) and 2000 HU (for the prosthetic ring) were derived from the respective CT densities. Hypodense artifacts were most for the St Jude valve, about twice the volume of hypodense artifacts associated with the Medtronic Hall valve, due to the nickel alloy in the prosthetic ring. Hyperdense artifact volumes were most for the St Jude valve, followed by the ON-X valve, the Medtronic Hall valve and least for the Carbomedics valve. Although the nickel alloy
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structure was found responsible for the St Jude valve, the large leaflet volume of the ON-X valve due to the steepest closure angle was responsible for the high hyperdense volume.

Leaflet motion affected hypodense and hyperdense artifacts and caused sharp increases during phases of rapid leaflet motion. The least artifacts were found in the phases with closed leaflets. Interestingly, valve with closed leaflets generated much less hypodense artifacts in stationary conditions than in pulsatile conditions. This difference is probably accounted for by edge effects and motion and not, as is commonly believed, by beam hardening and photon starvation. In fact, the relative paucity of artifacts found in stationary valves, the role of motion be at least as important as physics-related interactions.

ACQUISITION PARAMETERS FOR PHV

In the following chapters, various ways to reduce PHV related artifacts and to improve image quality were explored using the in vitro model. In part, the approaches reflected the mechanisms responsible for metal-related artifacts in general including beam hardening, photon starvation, scatter, edge effects, noise and motion.

In chapter 7 the effect of table movement (pitch) and noise were explored by comparing axial acquisition using prospective ECG triggering to spiral acquisition using retrospective gating. Axial acquisition (i.e. prospective triggering) was found to reduce both hypo- and hyperdense artifacts in pulsatile PHV at three different frequencies. Although this effect was less outspoken at 75/min with a non-significant difference for hypodense artifacts for the St Jude valve, all other differences were highly significant. Despite similar image noise at 90/min an important decrease of artifacts with prospective triggering was found which suggests that noise reduction is not the mechanism responsible for the reduction of artifacts. The limited role of noise reduction was supported by the very modest effect on PHV artifacts achieved with iterative reconstruction of raw data which provides for significantly lower image noise (chapter 8). It did allow, however, to achieve a similar level of artifacts with almost a 50% decrease in radiation exposure. Subsequently, in chapter 9 the relative reductions in PHV-related artifacts for static valves were compared between different photon energies and different image reconstruction algorithms. Three tube voltage settings (at 100, 120 and 140 kV) at equal total dose (CTDInvol) were compared using three different image reconstruction algorithms: filtered back projection, iterative image reconstruction, metal artifact reduction filter, and a combination of iterative reconstruction and metal artifacts reduction filter. In these experiments where only static valves were used, higher photon energy and iterative reconstruction reduced hyperdense artifacts by 2-4% each. Higher photon energy reduced hypodense artifacts by 31% (Medtronic Hall) and 36%
(St Jude) whereas the combination with iterative reconstruction resulted in 6 to 7% (St Jude) and 10 to 12% (Medtronic Hall) reductions. The metal artifact reduction filter induced secondary artifacts in all images and was therefore not found useful for the CT evaluation of PHV.

From the evidence presented above, the most effective (and most simple) ways to reduce PHV-related artifacts are 1) increased kV setting (i.e. increased photon energy) and 2) prospective triggering.

In chapter 10 the effectiveness of both increased kV settings and prospective triggering were tested for two transcatheter valves. In addition to measuring artifact volumes, a two-alternative blinded forced choice image quality test was used. Because the stent-frames of these two valves consisted of different alloys (Nitinol for the CoreValve, and a cobalt chrome alloy for the Sapien valve) the effect of both strategies was different. For the CoreValve, optimal image quality was achieved with prospective triggering irrespective of the kV used. Higher kV reduced hyperdense artifacts only, and prospective triggering reduced only hypodense artifacts. For the Sapien valve, best image quality was obtained with prospective triggering at high kV. Both artifact types were reduced with high kV but not with prospective triggering. Hence, different approaches to CT image acquisition may be dependent on the specific material properties of the transcatheter valve imaged and artifacts are only a single component among various factors that determine image quality.

In chapter 11, the influence of motion during the various cardiac phases was evaluated by measurement of the PHV velocity in the aortic root and relating the velocities to the variation of image quality during the cardiac cycle. The main findings of this study were: 1) PHV velocity during the cardiac cycle was least during end-systole (30 to 40% of the ECG interval) and mid-diastole (75 to 80% of the ECG interval), 2) these phases corresponded with, respectively, the best systolic and diastolic image quality when compared to the other cardiac phases, and 3) despite mid-diastolic velocities superior to end-systolic velocities at >90/min, the mid-diastolic image quality remained superior to systolic phases. Because of our findings, several recommendations for CT image acquisition of PHV could be made: 1) for good imaging results the use of heart rate lowering drugs such as beta blockers is warranted, 2) dose reduction techniques may be used for the ECG intervals associated with consistently inferior image quality relative to the other intervals (10, 20, 50 and 60%).
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FUTURE PERSPECTIVES

Optimizing image quality for CT imaging of PHV may be possible due to technological advances of CT technology. Further enhancement of image quality may require improvement of spatial resolution and low contrast detectability, and a reduction of noise and artifacts. To achieve superior image quality at a reasonable radiation exposure, several strategies have been explored. First, the detector width has expanded over the last decade and has led to the development of the 320 row detector which can cover the entire heart (16 cm) within a single heartbeat. For cardiac imaging, a larger detector width has no incremental value. Second, temporal resolution has been improved by reducing tube rotation time. Currently, the rotation time for a single source machine is limited by the excessive G forces acting upon the tube and therefore significant reductions in rotation time under 270 ms (and nominal temporal resolution under 135 ms) are unlikely. Alternatively, dual source machines circumvent this problem with two tubes orientated perpendicularly to each other and a consequent reduction of rotation time by half. The nominal temporal resolution will be reduced to approximately 70 ms. Third, novel image reconstruction algorithms may reduce noise, artifacts and may improve contrast and spatial resolution. These innovations were limited by the lack of computational power and the first generation of iterative reconstruction algorithms has been commercialized only recently. More complex algorithms for metal artifact reduction and motion correction still require too much time to be applied clinically and these algorithms are still limited by Moore's Law. Fourth, development of new detectors may improve image quality. Gemstone (i.e. Garnet) detectors will provide for better spatial resolution (high definition CT) and contrast. Furthermore, the introduction of spectral detectors may allow tissue differentiation. This increase in spatial (and spectral) resolution will further increase the data load.

Taking into consideration that all these possible enhancements for cardiac CT imaging are limited by the inability of current computer systems to handle the data loads associated with advanced reconstruction and postprocessing algorithms or new detectors, it is merely a question of time that such advanced systems become available. Making use of the currently available technology, an ideal system for PHV imaging would allow image acquisition without table movement, at high tube voltage, at an optimal temporal and spatial resolution, with a low radiation exposure and image reconstruction with an iterative metal artifact reduction algorithm. Whether such a system with a dual source 320-row gemstone detectors with second generation iterative image reconstruction will become commercially available within the next decade probably depends more on the viability of the common European currency than on patient needs.