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

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CHAPTER 1

Introduction

Based on: Habets J, Budde RP, Symersky P, van den Brink RB, de Mol BA, Mali WP, van Herwerden LA, Chamuleau SA. Diagnostic evaluation of left-sided prosthetic heart valve dysfunction. Nat Rev Cardiol 2011;8:466-478
Although many advances have been made in the design and construction of prosthetic heart valves since the first successful human valve replacements were performed by Starr and Edwards and Harken et al in 1960, none of the currently available prosthetic heart valves approach the human valve in either hemodynamic function or freedom from valve-related complications.

Since the first successful human valve replacements by Starr and Edwards\(^2\) and Harken et al\(^3\), valve replacement has become the standard of care for various valvular lesions. Standardization of the surgical procedure has made valve surgery widely practiced and has yielded good to excellent results. In 2003, approximately 290,000 patients worldwide underwent heart-valve replacement and received a prosthetic heart valve (PHV).\(^4\) The changing demographics of the patients and advances in surgical techniques have changed the practice. Valve repair is currently the preferred method in mitral-valve surgery, but the other valves, particularly the aortic valve, often require replacement with biological or mechanical valve prostheses in the majority of patients. Mechanical PHV have proven to be durable, but structural and nonstructural prosthesis dysfunction, or valve-related complications such as PHV thrombosis can occur with a reported incidence of between 0.01% and 6.0% per year.\(^5\) By contrast, biological valve dysfunction usually occurs as a consequence of valve degeneration, which requires reoperation approximately 15 years after PHV implantation.\(^6\) The variation in the frequency of such complications depends on the design of the study, the year the study was published, the type and position of the implanted valve, as well as the adequacy of oral anticoagulation therapy.\(^7\)\(^8\)

The success and widespread implementation of new therapies for valve disease are not only dependent on the new techniques and technology related to the procedure itself (e.g. reconstructive techniques for aortic and mitral valves, the valve-in-stent design and specific delivery systems for transcatheter valves) but also on the monitoring of the performance of these novel approaches and especially in relation to existing surgical techniques. Currently, the performance of these procedures is assessed with primarily cardiac echo-Doppler. In effect, the variation of valve-related complications may well depend on the technical evolution of cardiac echo-Doppler.

Cardiac echo-Doppler, or echocardiography, is a formidable tool that enables real time 2 and 3 dimensional evaluation of valves with excellent temporal and spatial resolution. As a technology, however, it has evolved considerably since the principle of echocardiography was described by Elder and Herts in 1954.\(^11\)\(^12\) For nearly two decades after that, echocardiography was limited to one-dimensional (M-mode) imaging.\(^13\) It was only after the development of a phased array scanner in the mid seventies that the technology for current-day two-dimensional imaging was possible.\(^14\)\(^15\) The use of Doppler to measure blood velocity only became commonplace in the early 80s\(^16\)\(^17\), and only recently the possibility to measure tissue velocity has been added.\(^18\)
In the above citation of Hammermeister et al.\textsuperscript{3}, a randomized trial was performed of Bjork Shiley mechanical versus porcine bioprostheses in order to establish the merits of each type of valve. No difference in survival was found. A surprisingly low incidence of endocarditis was observed. Taking into account that the inclusion of these patients ran from 1977 to 1981, one must relate their findings to the state of echo-Doppler technology at the time. In fact, one must conclude, that the diagnostic capabilities at the time were lacking by today’s standards to correctly evaluate the observed 10% mortality in the first postoperative year. Early prosthetic valve endocarditis, rapid degeneration of biological valves, severe patient prosthesis mismatch and other causes of obstruction may have been missed completely. Hence the measure and follow-up of procedural success is as reliable as the diagnostic modalities used for the follow-up. The evolution of echo-Doppler technology makes the comparison of this landmark trial to contemporary results difficult.

Currently, transthoracic and transesophageal echocardiography and fluoroscopy are used for the evaluation of PHV function.

Transthoracic echocardiography (TTE) is noninvasive, fast, readily available at the bedside, and cost-effective.\textsuperscript{18} Imaging in adults is performed with transducers operating at 2–3.5 MHz, providing a spatial resolution of 0.6–1.0 mm and an excellent temporal resolution of 15–60 ms.\textsuperscript{19} Anatomical information is obtained by B mode imaging. Doppler ultrasonography is an essential part of PHV evaluation, as it visualizes direction and velocity of blood flow. The transprosthetic mean pressure gradient can be determined using the modified Bernoulli equation.\textsuperscript{18,20} An increased transvalvular pressure can be a sign of PHV obstruction. In the measurement of pressure gradients, aligning the ultrasound beam as parallel as possible to the transprosthetic flow is important. The transvalvular gradient is determined by the effective orifice area (EOA) and the blood-flow rate, which, in turn, depends on the tissue oxygen demand related to body surface area (BSA). Therefore, knowing the size of the prosthesis, heart rate, and BSA is important to correctly interpret the transprosthetic pressure gradient measured by TTE.\textsuperscript{21} An increased transprosthetic pressure gradient might be caused by high stroke volume (because of low heart rate or paravalvular leakage), patient prosthesis mismatch, or obstruction by thrombus, pannus, or vegetations.\textsuperscript{21} Calculating the effective prosthetic valve area using the continuity equation is also important because multiple echocardiographic parameters will result in a more confident diagnosis.\textsuperscript{18,21,22}

Limitations of TTE include operator-dependency and poor acoustic windows resulting from either acoustic shadowing caused by the PHV material or TTE being performed in the early postoperative phase (within 1 week after PHV implantation) owing to postoperative influences such as pericardial effusion, or in specific patient groups, such as those with emphysema and obese individuals. Left-ventricular dysfunction and concomitant valvular disease can also influence the echocardiographic parameters.\textsuperscript{21}
Furthermore, the pressure recovery phenomenon and complex, fast, local blood flow can result in unreliably high measurements of transvalvular pressure gradient, which do not reflect the actual transvalvular pressure gradient and prosthetic EOA for diagnostic assessment of PHVs. However, an increased transvalvular gradient and/or decreased prosthetic EOA compared with baseline TTE Doppler measurements remain indicators for further evaluation of suspected PHV dysfunction, as stated in the consensus guidelines for evaluation of PHV with echocardiography. Three-dimensional (3D) TTE might have additional diagnostic value to two-dimensional (2D) TTE evaluation for PHV evaluation and can be considered in patients with inconclusive 2D TTE evaluation.

Transesophageal echocardiography (TEE) is a semi-invasive imaging technique for the evaluation of suspected PHV dysfunction. The proximity of the esophagus to the heart enables the TEE probe to be positioned close to the heart, without the interference of the lungs. Owing to its semi-invasive nature, a few absolute contraindications to TEE should be taken into account, including esophageal spasm, stricture, laceration, perforation, and diverticula. Although TEE is less convenient for patients than TTE, TEE offers better spatial resolution (0.2 mm) because the transducer operates at a higher frequency (usually 3.5–7.0 MHz). The high spatial resolution, close proximity of the probe to the anatomical structures, and the use of various probe angulations in TEE allow better visualization of anatomical abnormalities related to the PHV than with TTE. TEE can also be combined with visualization techniques using Doppler ultrasound. TEE is superior to TTE in the detection of leaflet thickening, leaflet prolapse, and flail cusps. Complementary to TTE, TEE can be useful for evaluation of PHV leaflet motion and assessment of regurgitation, especially in the mitral position. Acquisition and interpretation of TEE images are operator-dependent and require considerable experience.

3D TEE has been introduced in the past decade and has the potential to be of additional diagnostic value for evaluation of patients with PHV dysfunction. However, only case studies involving the use of this modality have been published thus far.

Fluoroscopy enables the noninvasive evaluation of the opening and closing angles of mechanical PHV leaflet(s), the motion of the leaflets and the PHV base ring, and the integrity of mechanical PHV components. Each mechanical type of PHV has a characteristic appearance on X ray images, with specific opening and closing angles. For adequate fluoroscopic evaluation, the patient must be positioned so that the leaflets of the mechanical PHV are positioned perpendicular to the X ray tube—a process that can be cumbersome, depending on specific valve orientations. Radiation exposure is limited (less than 1 mSv) as only a few heartbeats need to be visualized.
Fluoroscopy is superior to TTE and TEE for visualization of leaflet motion in the aortic position. In the mitral position, where more extreme tube angulations are needed, TEE and fluoroscopy demonstrate comparable results. Fluoroscopy has no role in biological PHV assessment because of the radiolucent aspect of the biological PHV leaflets.

Despite the widespread use and the enormous experience with echo-Doppler for the evaluation of PHV function, some limitations remain for the evaluation of dysfunctional PHV. These limitations have been well described by a report of Girard et al where the surgical findings for aortic prosthetic obstruction were compared to the preoperative diagnosis with echocardiography. In this series, up to 50% of the preoperatively determined cause of obstruction differed from the surgical findings. Therefore, echo-Doppler may be an effective tool to detect obstruction but often is not capable to identify the cause of obstruction. In another series, Faletra et al report that in some patients no surgical abnormalities were found where echo-Doppler had found signs of dysfunction. Therefore, in clinical practice, the shortcomings of echo-Doppler may provide a role for CT to aid in the diagnosis of prosthetic valve dysfunction. Due to the different technology, several possible advantages compared to echo-Doppler may be the uncoupling of acquisition and image evaluation, image postprocessing capabilities with assessment of the datasets in any chosen imaging plane, and a more complete overview of the anatomy. ECG-gated CT scans visualize the PHV in the different phases of the cardiac cycle. In most cases, the cardiac cycle is reformatted into ten evenly spaced phases. Leaflet motion can be evaluated in cine mode by looping images of the various reconstruction phases. The spatial resolution of CT (0.6 mm) is superior to TTE, but not to TEE. The temporal resolution of MDCT (90–180 ms for a 64-slice MDCT), however, is inferior to both TTE and TEE (15–60 ms). Postprocessing of the acquired CT data set allows static and dynamic reconstructions in every desired imaging plane.

CT technology has rapidly evolved in the last 20 years. The first CT conceived in the EMI laboratories in 1972 used axial image acquisition and reconstruction of a single transverse image of 80 x 80 pixels took seven minutes. The further evolution of CT technology was parallel to the increase in computational power (Moore's Law). For example, the very first image reconstruction algorithms were based on an algebraic reconstruction technique. With the introduction of an analytic reconstruction technique (filtered back projection) based on the mathematical principles developed by Johann Radon in 1917, a 160 x 160 picture could be reconstructed on the same computer in 30 seconds. Another important issue is the speed of image acquisition. At first, image acquisition was done by taking successive axial (transverse) slices with an incremental change in table position between each slice (Fig. 1). Axial single slice acquisition was prone to artifacts due to breathing. Spiral image acquisition allowing continuous table movement allowed image acquisition in a single breath-hold (Fig. 2).
From the 1980’s to present the performance of CT systems doubled every two years with the doubling of detector-rows and the parallel evolution of the computational power to match the data load.  

Several factors determine the performance of current CT systems: 1) detector width, 2) temporal resolution, 3) iterative reconstruction algorithms. Currently, the 320 and 256 detector-row systems are able to cover 16 (the entire heart) and 8 cm respectively in a single rotation. For cardiac imaging this results for an acquisition time of one and two heartbeats with consequent impressive reduction of radiation exposure. Additional reduction of radiation exposure may be achieved with wide coverage by axial imaging of a single preselected cardiac phase (i.e. prospective triggering, Fig 3a) instead of conventional spiral image acquisition with the use of retrograde ECG gating (e.g. allotting image data to particular phases of the ECG interval after acquisition Fig 3b).
The temporal resolution of a single source (single tube) system is limited by the rotation time of the tube. Further reduction of a rotation time of 270 ms of current 256 detector-row systems (achieved with an air-bearing) is curtailed by excessive G forces (29 G). A method to circumvent this problem is to place two energy sources in a single system which halves the rotation time and may achieve a temporal resolution of 70 ms. The innovation of iterative image reconstruction techniques represent in fact a revival of the algebraic image reconstruction used in the very first CT systems which had been discontinued due to lack of computational power. Whereas a further increase in anatomical coverage confers no advantage to cardiac imaging and faster rotation times are simply not possible due to excessive G forces, more sophisticated reconstruction algorithms depend on computational power.

Recently, a panel of experts has designated the use of ECG-triggered CT as appropriate in the setting of suspected prosthetic valve dysfunction with equivocal echocardiographical results. Despite the technical prowess of state-of-the-art CT systems, little evidence is currently available to support this claim. In fact, this designation may be more motivated by the need for alternatives besides echocardiography since there is a dire lack of specific acquisition, post-processing and evaluation protocols for PHV with CT.

The work described in this thesis attempts to find the indication for CT in the evaluation of PHV function. At first, we tested whether CT imaging in selected patients suspected of prosthetic obstruction yielded additional information that may aid in clinical decision making (chapter 2). A case of PHV dysfunction in a patient with three and subsequently four PHV illustrates the usefulness of CT and its complementary value to echocardiography. (chapter 3). Then, we performed a survey of all patients with PHV that had undergone cardiac ECG-gated CT imaging to establish which valves would benefit from CT imaging (chapter 4). In order to study various acquisition protocols an
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in vitro model was developed and the baseline characteristics of commonly encountered PHV are described (chapter 5). For the in vitro comparison of acquisition protocols, the radiopaque anatomy of four commonly used mechanical PHV was characterized. Using the CT densities of the various valve components, various thresholds are proposed for the measurement PHV-related artifacts. Furthermore, the effect of leaflet motion on these artifacts was measured (chapter 6). In an effort to further understand the generation of PHV-related artifacts, retrospectively ECG-gated (spiral) acquisition is compared to prospectively triggered (axial) acquisition in the in vitro model (chapter 7). The possibility of reducing radiation exposure while retaining image quality with the use of iterative reconstruction is evaluated (chapter 8). Furthermore, different CT tube settings in addition to various image reconstruction and postprocessing algorithms such as a metal artifact reduction filter and an iterative reconstruction algorithm are evaluated for the reduction of PHV-related artifacts (chapter 9). Considering the findings with mechanical PHV, four modes of acquisition are tested in vitro for transcatheter valves with quantification of noise, artifacts in addition to blinded side-by-side comparison of image quality (chapter 10). In an attempt to quantify the effect on motion during the cardiac cycle on CT image quality, the motion and instantaneous velocity of PHV was quantified in retrospectively gated datasets of clinical patients and correlated to image quality as determined by blinded side-by-side comparison (chapter 11). Chapter 12 summarizes the findings is this thesis and gives an overview of the current CT technology and the newest technological developments.
REFERENCES


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