

Yale University

EliScholar – A Digital Platform for Scholarly Publishing at Yale

Yale Medicine Thesis Digital Library

School of Medicine

January 2011

Multi-Modal Imaging Evaluation Of The Aortic Root: Ecg-Gated And Non-Ecg-Gated Computed Tomography Versus Echocardiography

Elie Rashid Balesh

Yale School of Medicine, elie.balesh@gmail.com

Follow this and additional works at: <http://elischolar.library.yale.edu/ymtdl>

Recommended Citation

Balesh, Elie Rashid, "Multi-Modal Imaging Evaluation Of The Aortic Root: Ecg-Gated And Non-Ecg-Gated Computed Tomography Versus Echocardiography" (2011). *Yale Medicine Thesis Digital Library*. 1538.
<http://elischolar.library.yale.edu/ymtdl/1538>

This Open Access Thesis is brought to you for free and open access by the School of Medicine at EliScholar – A Digital Platform for Scholarly Publishing at Yale. It has been accepted for inclusion in Yale Medicine Thesis Digital Library by an authorized administrator of EliScholar – A Digital Platform for Scholarly Publishing at Yale. For more information, please contact elischolar@yale.edu.

Multi-modal Imaging Evaluation of the Aortic Root:
ECG-gated and Non-ECG-gated Computed Tomography versus Echocardiography

A Thesis Submitted to the
Yale University School of Medicine
in Partial Fulfillment of the Requirements for the
Degree of Doctor of Medicine

by

Elie Rashid Balesh

2011

Abstract

The main diagnostic imaging modalities currently used to image the aortic root and ascending aorta include transthoracic echocardiography (TTE) and either ECG-gated or non-ECG-gated computed tomography (CT), each with its respective advantages and disadvantages. This study aimed to examine the reproducibility and agreement of inter-reader measurements of the aortic root made on all three imaging modalities. The results of this study revealed that inter-cardiologist measurements of the aortic root performed on echocardiography lack reproducibility (mean difference of 2.9 ± 5.76 mm). Aortic root measurements made on ECG-gated CT studies more closely agree with measurements made on echocardiography than do those made on non-ECG-gated CT studies (mean differences of 0.4 ± 3.93 mm versus 0.9 ± 5.92 mm in the axial dimension and -0.2 ± 3.82 mm versus 1.1 ± 5.46 mm in the orthogonal dimension). When a single radiologist reviews a set of both ECG-gated and non-ECG-gated CTs, the mean difference of axial aortic root measurements is small (-0.6 ± 1.99 mm). However, when aortic root measurements are made by two different radiologists, there is a much greater increase in mean difference for non-ECG-gated CT studies (-2.4 ± 6.32 mm) as compared with ECG-gated CT studies (0.3 ± 3.06 mm), suggesting that ECG-gating, which produces higher resolution images, buffers the amount of bias and variation that are introduced by inter-radiologist differences in measurement methods. Finally, review of radiologists' cardiac CT reports revealed poor standards and high non-uniformity in providing referring clinicians with relevant aortic measurements that have an important impact on patient care. A number of concluding recommendations are made and discussed to increase the value added by an institution's cardiac radiology service.

Acknowledgements

I would like to acknowledge and thank my thesis advisor, Dr. Hamid Mojibian, M.D., for his academic guidance and support for this research project. I would like to acknowledge and thank Dr. Perry Choi, M.D., Fellow in the Section of Cardiac Radiology, and Dr. Paras Bhatt, M.D., Fellow in the Section of Cardiology, for their enthusiastic participation in this research project. Without their imaging expertise and dedicated time and effort, this study would not have been possible. I would like to thank Lawrence Staib, Ph.D., for his very helpful advice on choosing the appropriate statistical methods for our data analysis. Finally, I would like to thank librarian Janis Glover at the Yale Cushing/Whitney Medical Library for her help with performing a thorough search and review of the published literature on aortic root imaging.

Table of Contents

Introduction.....	1
Methods.....	16
Results.....	21
Discussion.....	47
References.....	55

Introduction

The evaluation of aortic root pathology via diagnostic imaging has proven challenging for radiologists, cardiologists, and cardiothoracic surgeons alike. Clinical decisions surround medical, interventional, or open surgical management are often made without sufficiently accurate imaging data to characterize the state or progression of various aortic root abnormalities, including aortic annular ectasia or aneurysmal dilation, aortic valvular insufficiency, aortic valvular stenosis, congenital aortic valvular structural abnormalities, as well as other conditions, such as blunt thoracic trauma involving the proximal aorta, and post-operative surveillance of prosthetic heart valves. Much controversy exists surrounding the radiologic examination of the aortic root, beginning with the technicalities surrounding the definition of the term “root,” to the various modalities used to image it, to how to best geometrically measure various aspects of it in two and three dimensions. The modalities used to image the aortic root and ascending aorta include transthoracic echocardiography (TTE), transesophageal echocardiography (TEE), ECG-gated or non-gated cardiac computed tomography (CT), and cardiac magnetic resonance imaging (MRI). The main modalities currently used in routine clinical practice are TTE and non-ECG-gated CT, with ECG-gated CT and cardiac MRI reserved for more cases requiring more advanced clinical work-up. Each modality has its respective advantages and disadvantages, and non-uniform image acquisition and reformatting protocols, aortic root definitions and measurement methods, and reporting standards are used by different radiologists and/or cardiologists at different institutions.

Anatomically, the aortic root forms the bridge from the left ventricle to the ascending aorta, and it functions as the structural support apparatus for the aortic valve.

The histologic boundary that divides the left ventricle from the ascending aorta lies at the point where ventricular tissue transitions to the fibroelastic tissue of the arterial trunk, but this point does not coincide with the site of attachment of the aortic valve leaflets (1). The semi-lunar attachments of the valve leaflets form the hemodynamic junction and are responsible for maintaining the pressure gradient between the left ventricle and the aorta (1). The component anatomical structures that altogether constitute the aortic root apparatus include the sinutubular junction, sinuses of Valsalva, leaflet attachment sites, inter-leaflet triangles, the aortic leaflets themselves, the ventriculo-arterial junction, and the left ventricle outflow tract (1). Cardiothoracic surgeons often make reference to the “aortic annulus,” but this is a non-existent anatomical structure, as the insertion of the aortic leaflets into the aortic root simulates a crown-like shape, but no distinctive tissue exists at the site of leaflet insertion (2). This confusion arises in part from the limited anatomic information gathered from two-dimensional echocardiographic and angiographic studies of a truly three-dimensional and complex geometric valve apparatus (2). What is commonly reported as the measurement of the aortic root is the diameter of the aorta at the level of the sinuses of Valsalva as seen in reformatted oblique images, and aortic root dilatation commonly defined as a diameter of greater than 40 mm (1).

The presence of an abnormal aortic root in a patient is highly predictive of the presence of other concomitant aortic pathologies, such as thoracic and abdominal aortic aneurysms (3). This is likely due to the shared risk factors of increased age, smoking, hypertension, diabetes mellitus, and dyslipidemia, as well as similar pathophysiological mechanisms, such as cystic medial degeneration due to structural abnormalities in

collagen or elastin, or atheromatosis and its associated inflammatory degradation of arterial walls (3).

Thoracic aortic aneurysms are usually asymptomatic, often detected incidentally on an imaging study of the chest performed as part of some other clinical investigation. The times at which thoracic aneurysms themselves become symptomatic are usually catastrophic, during rupture or significant dissection with or without involvement of the aortic valve. The incidence of thoracic aortic aneurysm disease is on the rise, but it is unclear whether this rise is due to an increase in incidental detection and reporting, or due to a true organic increase in the disease at relatively constant rates of detection and reporting (4). The most recently available (2007) data from the Centers for Disease Control and Prevention ranks “Aortic Aneurysm” the nineteenth most common cause of death among all age groups, accounting for 12,896 deaths a year, and the fifteenth most common cause of death in individuals age fifty-five and older (5). Although the outcome of untreated thoracic aneurysm disease is likely to be fatal rupture or dissection, the disease process itself is indolent, and provides many opportunities for detection and intervention to change outcomes. Two-dimensional transthoracic echocardiography has traditionally been used for initial evaluation and subsequent follow-up measurements of thoracic aortic aneurysms. Mathematical modeling of the natural history of aortic aneurysm disease has revealed that an individual with an asymptomatic thoracic aortic aneurysm incurs a 34% lifetime risk of rupture or dissection by the time that his or her ascending aorta reaches a diameter of 6 cm (4). Cardiothoracic surgeons will recommend intervention at a diameter of 5.5 cm, or 5.0 cm for patients with Marfan Syndrome,

bicuspid aortic valve, or family history of aortic dissection; patients with symptomatic aneurysms should be intervened on regardless of aneurysm diameter (4).

Disorders of the aortic valve itself, such as sclerosis with or without stenosis, and insufficient commissural closure resulting in regurgitation, are highly prevalent and have traditionally been evaluated with transthoracic two-dimensional echocardiography and treated via open surgical implantation of a prosthetic mechanical valve. Aortic stenosis is the most common native valve disease, with increasing prevalence among the aging population of the United States (6). Approximately 5% of individuals over the age of 65 in North America and Western Europe have some degree of degenerative aortic stenosis (7). Current guidelines by the American College of Cardiology and the American Heart Association define severe aortic stenosis when aortic valve area is less than 1 cm^2 , moderate aortic stenosis as valve area between $1-1.5 \text{ cm}^2$, and mild aortic stenosis as greater than 1.5 cm^2 but less than the normal valve area predicted for a patient's age, gender, and body surface area (8). The aortic valve area is usually assessed by the 2D derived continuity equation, which is based on certain assumptions that often result in not insignificant measurement errors that can impact the decision whether or not to perform surgery, choice of mechanical valve device, and the likelihood of post-implantation valve complications, such as paravalvular leak (6). The continuity equation assumes a circular geometry of the left ventricular outflow tract (LVOT) with laminar fluid flow of uniform velocity across the LVOT; however, in a large percentage of elderly patients with severe aortic stenosis, a "sigmoid septum" is present, in which asymmetric basal septal hypertrophy results in non-circular and sometimes highly irregular geometry of the LVOT (6). In addition, the flow through the LVOT usually is non-laminar due to

hyperdynamic function of a hypertrophied left ventricle or due to anatomic obstruction due to hypertrophied subaortic interventricular septum, both of which create turbulence and non-uniform flow velocities (6).

Besides patient risk stratification, accurate imaging of the aortic root and proximal ascending aorta has proven especially important for the performance of fluoroscopy-guided thoracic endovascular aneurysm repair (TEVAR) and the emerging practice of transcatheter aortic valve implantation (TAVI), as opposed to traditional open surgical repair or replacement performed via open thoracotomy (9). Clear, accurate three-dimensional imaging obtained via multi-detector computed tomography (MDCT) angiography is crucial for aneurysm characterization, candidate patient selection, stent-graft device selection that best fits with the anatomy of the lesion, as well as pre-operative formulation of a plan for the intervention (10). Similarly, multi-slice computed tomography (MSCT) enables a comprehensive anatomic evaluation of the aortic root, including the precise geometry of the aortic valve and its “annulus,” the presence of dystrophic calcification, and the relationship of the valve to important surrounding structures, such as the ostia of the coronary arteries, which can become occluded both pre- and post-operatively by a bulky aortic cusp (6).

Echocardiography is traditionally regarded as the de facto “gold standard” imaging modality for assessment of the cardiac valves and chambers, and it is routinely performed during the initial clinical workup of patients suspected of having structural cardiac and/or aortic pathologies (11). TTE and TEE spare the patient from receiving ionizing radiation and are relatively inexpensive to perform, but image quality and reproducibility are highly dependent on operator experience and skill. While they both

provide very good temporal resolution of the beat-to-beat motion of the aortic valve apparatus, along with the ability to visualize flow dynamics across the aortic valve via Doppler imaging, they are each limited in terms of spatial resolution and extent of anatomic views (4). TTE image quality is highly dependent on patient body habitus, and it is only capable of visualizing the proximal portion of the ascending aorta up to the level of the sinotubular junction, thus missing any sites of pathology at the mid-ascending aorta and higher (4). TEE image quality is often superior to that of TTE because it is not related to patient body habitus, but it is an invasive procedure done under anesthesia; moreover, it provides a limited visualization of the ascending aorta due to image distortion imposed by the intervening tracheal air column (4).

In recognition of the poor inter-observer reproducibility of echocardiography measurements, in 1978, the American Society of Echocardiography sought to establish quality control and measurement standardization criteria to govern how echocardiography should best be performed and how specific cardiac structures should best be measured. With regard to the aortic root, the publication stated the following:

The Committee recommends that the aortic root be measured by the leading edge methodology - outer/inner; from the anterior portion of the anterior aortic wall to the inner or anterior-most boundary of the posterior aortic wall and only after a mitral/aortic sweep and in an area where at least two aortic cusps are visualized to reduce the potential for angulation error. The aortic tracing should be marked on the record by the technician when he or she has completed the sweep and finds his/her hand perpendicular to the chest wall when recording the aorta. Since aortic interfaces are often less clear in systole because of angulation, and in consideration of variable expansion of the aortic root in systole, the aortic root should be measured at end-diastole at the onset of the first rapid deflection of the QRS complex of the ECG (12).

In 1995, the Framingham Heart Study sought to establish reference values for aortic root diameter in healthy adult human subjects without evidence of aortic disease

using M-mode TTE. It was determined that age was the most important determinant of aortic root size in both men and women in the multivariable regression models (13). In a study sample size of 1,433 men (mean age 46 ± 13 years) and 1,816 women (mean age 47 ± 13 years), the aortic root diameters were measured to be 32 ± 3 mm and 28 ± 3 mm, respectively (14).

Sixty-four-slice multi-detector row computed tomography (MDCT) of the aortic root can be performed with or without ECG-gating to correct for the significant amount of motion artifact produced by the changes in aortic size during the systolic and diastolic phases of the cardiac cycle. Non-gated cardiac CT is more commonly performed than its ECG-gated counterpart, due to the limited availability of costly gating-capable scanners, and because gated studies are associated with a significantly higher radiation dose imparted to the patient. The radiation doses with retrospectively ECG-gated and non-ECG-gated scanning of the thoracic aorta are approximately 8.85 mSv and 4.5 mSv, respectively (15). Despite the use of ECG-gating to correct for changes in the diameter of the aortic root, cardiac CT is inherently limited to taking images along the axial plane, which often fails to capture the true geometry of the aortic annulus as it moves along oblique planes and into a more vertical orientation during the cardiac cycle (4). Even though modern CT scanners are capable of rendering reconstructions in sagittal and coronal planes in addition to the acquired axial images, the resolution in the non-axial reconstructions is often insufficient to allow accurate assessment of aortic shape or diameter, always leaving some degree of uncertainty in measurements made of the aortic root (4). Although CT imaging provides detailed structural information about the cardiac valves, especially the aortic valve and its supporting anatomic structures within the aortic

root, cardiac CT is unable to provide useful information regarding flow dynamics across cardiac valves in the clear format that Doppler echocardiography studies do (11). What may structurally appear to be valvular stenosis dilation by diameter or planimetric area measurements does not guarantee the presence of altered hemodynamic flow across the valve, such as turbulence or regurgitation (11). In addition to identifying structural abnormalities within the heart, valves, and great vessels, cardiac CT imaging has the additional advantage of being able to qualitatively and quantitatively assess coronary artery calcification as a marker of coronary artery disease, as well as an independent risk factor and accurate predictor of adverse cardiovascular patient outcomes (16). In a clinical study of thirty-four patients with asymptomatic aortic stenosis, patients were evaluated using the following clinical parameters: aortic valve calcium (AVC) score as quantified with MSCT; echocardiographic parameters, including aortic valve area calculated with continuity equation, mean and maximal transvalvular pressure gradients, and end-diastolic septal wall diameter; and laboratory tests, including serum levels of brain natriuretic peptide (BNP) and C-reactive protein (CRP). Within 18-24 months of follow-up, eleven of the thirty-four patients developed a major adverse clinical outcome, including one patient who died from sudden cardiac death and ten who required aortic valve replacement surgery due to hemodynamic progression and symptom onset. Of those ten patients requiring surgery, six completed the surgery successfully; one patient did not consent to the operation; and three patients were deemed poor surgical candidates and were thus not offered the operation, one of whom died shortly thereafter. Among all imaging and laboratory parameters measured, the aortic valve calcium score was the strongest predictor of adverse clinical outcome; other statistically significant predictors

were aortic valve area, mean transvalvular pressure gradient, and serum BNP level (16). The authors of the study concluded that in patients with severe aortic valve calcification, close follow-up examinations are mandatory, and early elective aortic valve replacement surgery may be considered even in the absence of symptoms.

Cardiac MRI provides excellent spatial resolution of the soft tissue structures of the cardiac chambers, valves, and great vessels. In addition, because MRI is inherently a multi-plane modality that acquires images in axial as well as sagittal and coronal planes, highly accurate measurements of the aortic root are possible because image resolution is not sacrificed during reconstruction (17). The high image quality of soft tissue structures obtained via MRI enables superior clinical evaluation of a number of pathologies related to the heart, valves, and great vessels, especially congenital malformations in pediatric patients. Atrial and ventricular septal defects, valve cusp abnormalities, conotruncal malformations (truncus arteriosus, transposition of the great vessels, tetralogy of Fallot, double-outlet right ventricle, situs inversus totalus, etc.), and cardiac tumors can all be more clearly and accurately evaluated with cardiac MRI as compared to cardiac CT and echocardiography (18). One of the most important advantages of cardiac MRI as compared to cardiac CT is its lack of high-dose ionizing radiation imparted to patients, which is especially important when considering imaging of pediatric and pregnant female patients. In contrast to cardiac CT, which lacks the ability to provide information regarding trans-valvular hemodynamics, velocity flow mapping measurements can also be obtained with cardiac MRI in a more quantitative manner than with Doppler echocardiography (17). Despite all of the positive aspects of cardiac MRI, its routine clinical use in the evaluation of cardiac patients is currently limited by its expensive cost,

limited availability, lengthy and uncomfortable study time, and the high prevalence of patients with implanted MR-incompatible cardiovascular devices.

Because there is no true anatomic structure known as the “aortic annulus” which can be imaged, and because serial axial images on CT and MRI do not follow the course of the normally tortuous aortic lumen, much controversy exists in the cardiac radiology community as to how to best image the aortic root and proximal aorta using various forms of multi-planar image reconstruction. Unlike for echocardiography, no official academic or professional committee has formally studied the issue and published recommendations, guidelines, or standardization criteria by which radiologists should measure the aortic root or proximal aorta on CT and/or MRI. Various software packages are able to perform oblique or double-oblique reconstructions that provide cross-sectional images that are perpendicular to the long axis of the aortic lumen, but inter-radiologist disagreement regarding the use of aortic valve cusp-cusp versus cusp-commissure diameters can produce clinically significant differences in the bottom-line size of the aortic root (19). Similarly, in measuring the various diameters along the ascending aorta, disagreement exists as to whether or not the walls of the aorta should be included in the diameter, or if this value should be limited to the diameter of the lumen alone (19).

Using ECG-gated MDCT angiography, a Swiss study sought to establish normative measurement values for aortic parameters in healthy adult human subjects without evidence of aortic disease. In this study of 59 men (mean age 54.7 years) and 18 women (mean age 54 years), the mean diameter of the left ventricular outflow tract was found to be 20.3 ± 3.4 mm; at the level of the coronary sinus, 34.2 ± 4.1 mm; at the sinotubular junction, 29.7 ± 3.4 mm; and at the mid-ascending aorta, 32.7 ± 3.8 mm (20).

Coefficients of variation ranged from 12% to 17%, and the antero-posterior and transverse diameters of the ascending aorta varied 8.4% and 7.3%, respectively, during the cardiac cycle (20). The authors concluded that there were large inter-individual variations in diameters but with limited intra-individual variations during the cardiac cycle.

An English clinical study sought to establish normative measurement values for aortic parameters in healthy adult human subjects without evidence of aortic disease using cardiac MRI. In this study of 60 men (mean age 49.3 ± 17.2 years) and 60 women (mean age 49.2 ± 16.6 years), diastolic cusp-commissure measurements of the aortic root predictably correlated with patient age and body surface area, and moreover, were found to correspond closely with reference echocardiographic root measurements as reported in the Framingham cohort (19). Diastolic cusp-commissure dimensions were found to be 32.0 ± 3.5 mm in men and 28.4 ± 2.8 mm in women (19).

Comparison of the results obtained via TTE, ECG-gated cardiac CT, and cardiac MRI in the above mentioned studies reveals general agreement that the aortic root in healthy adults measures approximately 32 mm. However, each of these studies used only one imaging modality on its patient population, with no one patient having his or her aortic measurements taken with two or all three modalities for cross-comparison. One study has directly compared measurements obtained with TTE and retrospectively ECG-gated CT angiography performed within two months of one another on a single study population being evaluated for paroxysmal atrial fibrillation. Fifty-one men (mean age 56.6 ± 8.4 years) and 17 women (mean age 59.3 ± 9.3 years) were included in the study. The average aortic root diameter measured by TTE was 33 ± 4.1 mm; on CTA it was

36.9 ± 3.8 mm (1). The median difference between the two measurements was 3.9 mm, which was significant. The study concluded that TTE measurements are substantially lower or even normal in patients found to have dilated aortic root by CTA (1).

A different study sought to compare measurements of aortic valve area obtained with coronary CT angiography and transthoracic echocardiography and to determine whether differences in these estimates are related to underestimation of the area of the left ventricular outflow tract (LVOT) measured with echocardiography. The study population consisted of 41 men and women with a mean age of 58 ± 15 years who had undergone both studies within a 60-day period. Aortic valve area was measured with direct planimetry on coronary CTA images, and it was computed with the continuity equation after TTE. To determine how much of an effect LVOT measurements have on the output of the continuity equation, aortic valve area was recomputed with substitution of the LVOT area and diameter measured on coronary CTA images for the dimensions obtained from TTE. Aortic valve area measured with CT planimetry (mean 3.1 ± 1.4 cm²) was greater than that computed with TTE (mean 2.5 ± 1.3 cm²), and the 0.6 cm² difference in area was statistically significant (21). The study concluded that aortic valve area measured with CT planimetry is significantly greater than that calculated with TTE and the continuity equation, and that difference is at least partially related to differences in LVOT area based on LVOT diameter versus direct planimetry of the LVOT area (21).

Another study compared measurements of aortic valve area in patients with aortic stenosis using three imaging modalities: dual-source computed tomography, transthoracic echocardiography, and cardiac catheterization. A total of 50 patients (mean age 73 ± 10 years) with suspected aortic stenosis were included in the study. The mean aortic valve

area measured using DSCT was $1.16 \pm 0.47 \text{ cm}^2$ compared to a mean AVA of $1.04 \pm 0.45 \text{ cm}^2$ using TTE and $1.06 \pm 0.45 \text{ cm}^2$ using catheterization (22). These findings corroborate those reported above by Halpern, et al., which show that aortic valve area measurements obtained via CT are consistently greater than those obtained by TTE.

A similar study compared measurements of aortic valve area obtained with ECG-gated MDCT and TTE or TEE in patients with aortic regurgitation, instead of aortic stenosis. The study population included 45 adult patients of mean age 53 years who received both the CT and echocardiography studies within a time period of 60 days. The results of the study showed that in the 14 patients found to have mild aortic regurgitation by TTE, the aortic valve orifice area was $0.18 \pm 0.13 \text{ cm}^2$ by CT and not reliably measurable by TTE; in the 15 patients with moderate aortic regurgitation by TTE, the aortic valve orifice area was $0.36 \pm 0.23 \text{ cm}^2$ by CT and $0.26 \pm 0.04 \text{ cm}^2$ by TTE, a statistically significant difference; and in the 16 patients with severe aortic regurgitation by TTE, the aortic valve orifice area was $1.00 \pm 0.51 \text{ cm}^2$ by CT and $0.53 \pm 0.23 \text{ cm}^2$ by TTE, a difference that was also statistically significant (23). It is concluded from these data that CT is the more sensitive modality to evaluate the aortic valve orifice in patients with suspected or confirmed mild aortic regurgitation, as echocardiography is unable to provide accurate measurements (23). These findings are in agreement with those of the prior two studies, which show that CT measurements tend to report larger areas for the aortic valve orifice than those obtained via echocardiography.

A meta-analysis that included nine studies with an aggregate sample size of 175 women and 262 men (mean age 68.8 ± 4.2 years) with aortic stenosis who underwent aortic root imaging with MDCT and TTE revealed that the mean aortic valve area as

measured by CT was $1.0 \pm 0.1 \text{ cm}^2$; the mean aortic valve area as measured by TTE was $0.9 \pm 0.1 \text{ cm}^2$; and the mean difference was reported to be statistically significant at $0.03 \pm 0.05 \text{ cm}^2$ (7). The correlation between CT and TTE measurements was found to be strong ($r = 0.89$), suggesting a close agreement between the two imaging modalities (7). The results of this meta-analysis are in disagreement with those of the prior two studies, which reported consistently larger aortic valve area measurements by CT as compared to TTE.

The studies discussed thus far have all been concerned with imaging of the native aortic root, either healthy or diseased. Only one study has paid particular attention to the comparison of MDCT and TTE with regard to the imaging of the prosthetic aortic root, that is to say, for post-operative follow-up of patients for complications related to their mechanical aortic valves. During routine follow-up, patients received both MDCT and TTE for monitoring of the development of complications, such as pannus formation, suture loosening, paravalvular leak, and pseudoaneurysm formation. If there were positive findings of such complications on either imaging modality, the patients were consented for surgical reoperation, and the pathologic findings at surgery were compared to those predicted by both imaging modalities. Of the sixteen patients with prosthetic mechanical aortic valves, four patients were taken back to the operating room for redo surgery (24). MDCT correctly identified 100% of the complications confirmed by surgical pathology findings (24). TTE correctly identified 75% of the complications confirmed by operative findings; in one patient, suture loosening of the prosthesis with paravalvular leak was missed and mistakenly reported as a normally functioning mechanical valve (24).

The hypotheses and specific aims of the present study are to: 1) Demonstrate that clinically significant variation exists in inter-cardiologist measurements of the aortic root using TTE; 2) Demonstrate that measurements of the aortic root obtained by non-ECG-gated cardiac CT imaging do not closely agree with those obtained via TTE on the same patients; 3) Demonstrate that measurements of the aortic root obtained via ECG-gated cardiac CT imaging do closely agree with those obtained via TTE on the same patients; 4) Demonstrate that measurements of the aortic root obtained via ECG-gated cardiac CT do not closely agree with those obtained via non-ECG-gated cardiac CT on the same patients; 5) Demonstrate that reader measurement confidence is higher for CT than TTE imaging; 6) Demonstrate that a substantial fraction of radiologists' cardiac CT reports currently fail to provide clinically relevant and important measurements of the aorta, particularly the aortic root. It is the goal of this study to produce helpful recommendations for the imaging community regarding the use of echocardiography, ECG-gated cardiac CT, and non-ECG-gated cardiac CT in the clinical work-up of aortic root pathology. An additional goal of this study is to demonstrate that current radiologists' cardiac CT reports are highly non-uniform in the information they contain and the methodology by which aortic root measurements are made, if at all. If cardiac CT is to provide clinically useful information to cardiologists and cardiothoracic surgeons to guide their interventions, protocols should be standardized to minimize variation in qualitative and quantitative measurements as reported by different radiologists.

Methods

Patient Selection and Study Population

We received an Institutional Review Board (IRB) approval from the Human Investigation Committee (HIC) to review patients' medical records for the purpose of our study. All data was collected in compliance with HIC guidelines and was saved on a password-protected, Yale-New Haven Hospital (YNNH)-owned computer located in the Cardiac CT/MR reading room only accessible to authorized personnel. Microsoft Excel spreadsheets were used to organize all patient protected health information (PHI), imaging study accession numbers, and recorded measurement data in compliance with the Health Insurance Portability and Accountability Act (HIPAA).

A database search of IDX Radiology system was performed for all thoracic CT angiograms performed during the preceding two years. All patients in the database had one or more diagnostic imaging studies of the chest performed as part of the clinical investigation of a variety of cardiovascular conditions, all of which were readily accessible via the YNNH Picture Archiving and Communications System (PACS).

The starting point for patient selection in the present study was the fact that all patients had received at least one transthoracic echocardiogram during clinical work-up or follow-up within 6 months of their thoracic CTA. The clinical indications for the studies were most often for evaluation of aortic dissection or for pre- or post-operative assessment of thoracic aortic aneurysms. Importantly, only patients with completely native aortic roots and ascending aortas were included in the study; any patient with a prosthetic aortic valve, thoracic aortic endograft, or any form of manipulation of the aortic root or ascending aorta were excluded from the study.

All echocardiography and CT reports were reviewed for the presence or absence of reported measurements of the aortic root, sinotubular junction, maximum ascending aorta, and any other measurements of the aorta that were made and reported. These previously reported measurements were later compared to new measurements made on the same imaging studies of the same patients by appointed clinical fellows.

Image Acquisition – Echocardiography

All transthoracic echocardiograms were obtained using either the Acuson Sequoia C512 or the Philips iE33 ultrasound machines by an experienced YNNH staff ultrasonographer. Complete two-dimensional (2D), M-mode, color and spectral Doppler studies were performed on each patient based on current imaging standards recommended by the American College of Cardiology (ACC). The second reviewer accessed the images on a dedicated archiving system. All reports were available through PACS.

Image Acquisition – Computed Tomography

All non-ECG-gated CT studies were performed on either a 16-slice or 64-slice multi-detector CT scanner (GE Medical Systems; Milwaukee, Wisconsin). Non-ECG-gated serial 2.5 mm axial images of the chest were obtained before and after intravenous infusion of 90-120 cc of Omnipaque or Visipaque contrast. All images were retro-reconstructed to 1.5 mm. Images were sent to a 3D workstation for post-processing, and multi-planar reformatting was performed by dictating physician.

For ECG-gated CT studies, a 64-slice multi-detector CT scanner (LightSpeed VCT; GE Medical Systems; Milwaukee, Wisconsin) was used to obtain prospectively ECG-triggered serial 0.625 mm axial images of the chest with 100 ms of padding before and after intravenous infusion of 90-120 cc of Omnipaque or Visipaque contrast. ASIR technology was utilized for maximum radiation dose reduction. Images were reconstructed at 75% of the cardiac cycle. Images were sent to a 3D workstation for post-processing, and multi-planar reformatting was performed by dictating physician.

Image Analysis – Echocardiography

A single clinical fellow in the YNHH Department of Cardiology with two years of experience interpreting echocardiograms was recruited to perform repeat measurements of the aortic root on all patients' echocardiography studies. The fellow was blinded to the previously reported measurements and to the clinical indication for the study. The technical quality of each study was assessed using the following parametric criteria: motion artifact was graded on a scale of 0, 1, 2, or 3, for none, mild, moderate, or severe, respectively; the image quality of the sinotubular junction was graded as 0, 1, or 2, for preserved, partially effaced, or fully effaced, respectively; the amount of aortic valve calcification, which may interfere with accurate measurement of the aortic root, was graded on a scale of 0, 1, 2, or 3, for none, mild, moderate, or severe, respectively.

Image Analysis – Computed Tomography

A single clinical fellow in the YNHH Department of Radiology's Section of Cardiac Imaging with four years of experience interpreting CT examinations was recruited to perform repeat measurements of the aortic root, sinotubular junction, and maximum diameter of the ascending aorta on all patients' CT studies. The fellow was blinded to the previously reported measurements and to the clinical indication for the study. Measurements of the aorta were performed on a Vital Images Workstation version 5.0 (Minnetonka, MN). Only the axial dataset was used for the axial measurements. For the orthogonal measurements, double-oblique planes were generated by the workstation, so that direct short-axis measurements could be made. For the aortic root, the sinus of

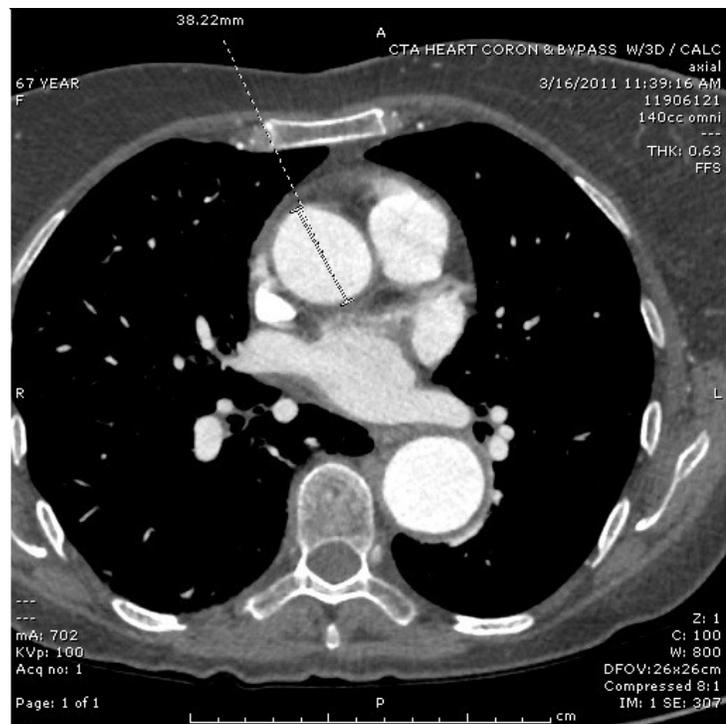
Valsalva was chosen. Three measurements were made for both the axial and orthogonal dimensions of the aortic root, and two measurements were made for both the axial and orthogonal dimensions of the sinotubular junction and maximum ascending aorta; the maximum values were selected for downstream analysis. Example CT images on the following page display how axial and orthogonal measurements of the aortic root were made. The technical quality of each study was assessed using the following parametric criteria: confidence in accurate identification and measurement of the root was graded on a scale of 0, 1, or 2, for unable to measure, poor confidence, or high confidence, respectively; ascending aorta motion artifact was graded on a scale of 0, 1, 2, or 3, for none, mild, moderate, or severe, respectively; the image quality of the sinotubular junction was graded as 0, 1, or 2, for preserved, partially effaced, or fully effaced, respectively; the amount of aortic valve calcification, which may interfere with accurate measurement of the aortic root, was graded on a scale of 0, 1, 2, or 3, for none, mild, moderate, or severe, respectively.

Statistical Analysis

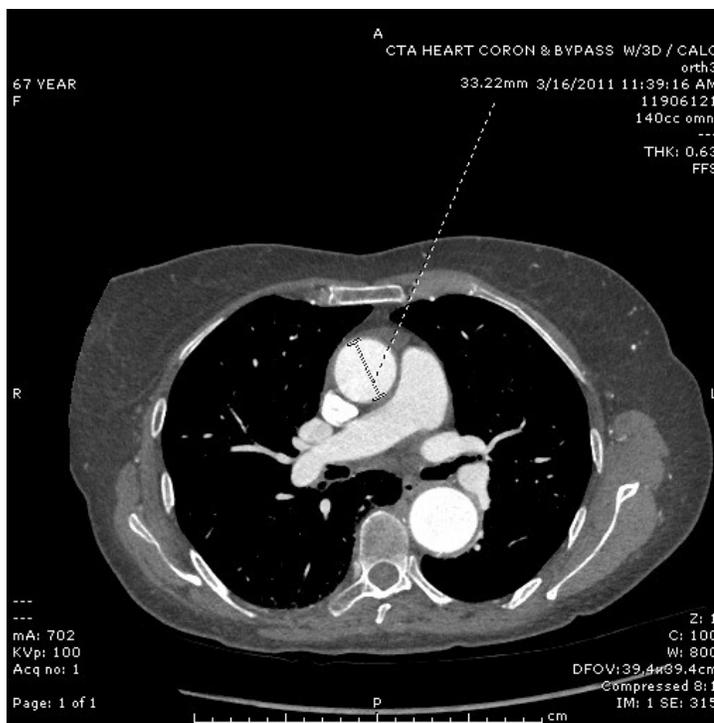
Consultation with the Department of Radiology's on-staff biostatistician was sought in order to determine the appropriate type of statistical analysis to perform on the dataset. Bland-Altman plots were used to analyze and display the agreement in aortic measurements amongst the multiple imaging modalities employed.



Example Image 1. Measurements of the aortic root made at the level of the sinuses of Valsalva in the orthogonal dimension on a reformatted oblique image obtained via non-ECG-gated computed tomography (CT).



Example Image 2. Measurement of the ascending aorta in the axial dimension obtained via ECG-gated computed tomography (CT). Note the ovoid geometry of the aorta in the axial plane.



Example Image 3. Measurement of the ascending aorta in the orthogonal dimension on a reformatted oblique image obtained via ECG-gated computed tomography (CT). Note the much more circular geometry of the aorta and the much smaller measurement value as compared to Example Image 2 (same patient).

Results

A total of 45 patients (overall mean age 58.8 ± 16.0 years, ranging from 19 to 84 years) were included in the study; broken down by gender, there were 32 males (mean age 56.3 ± 15.2 years, ranging from 19 to 78 years) and 13 females (mean age 64.9 ± 16.8 years, ranging from 36 to 84 years). The three subsets of patients were those who underwent TTE and only non-ECG-gated CT, those who underwent TTE and only ECG-gated CT, and those who underwent TTE and both forms of CT. A subset of 23 patients (overall mean age 63.1 ± 12.6 years, ranging from 42 to 82 years), composed of 13 males (mean age 62.3 ± 11.5 years, ranging from 42 to 78 years) and 10 females (mean age 64.2 ± 14.5 years, ranging from 42 to 82 years) had undergone TTE and non-ECG-gated CT studies within six months of one another. A subset of 14 patients (overall mean age 54.5 ± 20.2 years, ranging from 19 to 84 years), composed of 13 males (mean age 52.2 ± 19.1 years, ranging from 19 to 77 years) and 1 female (age 84 years) had undergone TTE and ECG-gated CT studies within six months of one another. A subset of 8 patients (overall mean age 54.0 ± 14.9 years, ranging from 36 to 82 years), composed of 6 males (mean age 52.3 ± 9.3 years, ranging from 42 to 64 years) and 2 females (mean age 59.0 ± 32.5 years, ranging from 36 to 82 years) had undergone TTE, ECG-gated CT, and non-ECG-gated CT studies all within a time period of six months of one another.

Prior and repeat measurements of the aortic root, sinotubular junction, and maximum ascending aorta obtained via echocardiography and both ECG-gated and non-gated computed tomography were analyzed for statistical agreement using Bland-Altman plots, also known as difference plots.

Comparison of prior and repeat measurements of the aortic root made via echocardiography (Fig. 1) revealed a mean difference of 2.9 ± 5.76 mm. Fifteen out of the forty (15/40, 37.5%) paired observations differed by ± 5 mm or more, which is considered a clinically significant difference to cardiothoracic surgeons. The cardiologist re-reading the echocardiography studies rated 13/40 as having “moderate” motion artifact, 14/40 with “mild” motion artifact, and the remainder having none; 14/40 studies showed “full effacement” of the sinotubular junction, 10/40 were “partially effaced”, and the remainder were preserved; and rated 2/40 studies as having “severe” aortic valve calcification, 4/40 with “moderate” calcification, 8/40 with “mild” calcification, and the remainder having none.

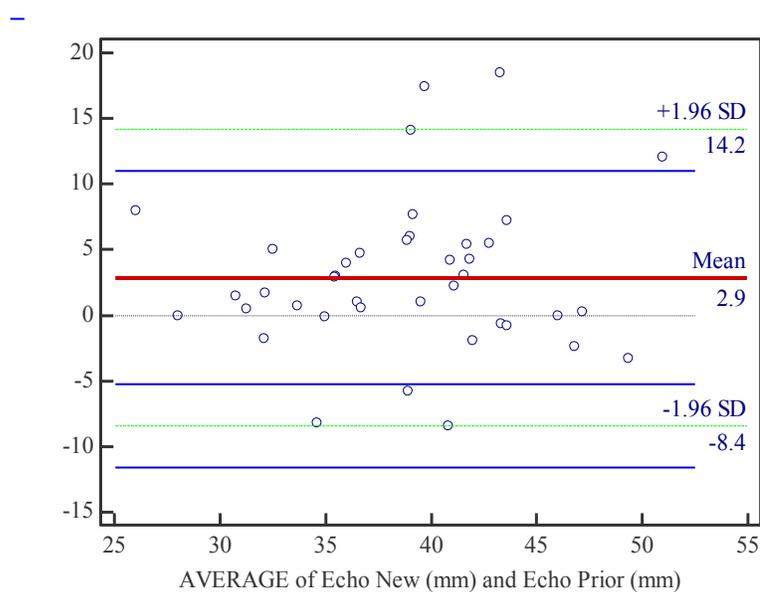


Figure 4. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made by a single cardiologist (Echo New) and those made by multiple different cardiologists (Echo Prior) on the same set of echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Aortic root measurements made in both axial and orthogonal dimensions on ECG-gated CT were compared with the measurements made on repeat echocardiography measurements. For the axial dimension (Fig. 2), there was a mean difference of 0.4 ± 3.93 mm, with three out of the nineteen (3/19, 15.7%) paired observations differing by ± 5 mm or more. For the orthogonal dimension (Fig. 3), there was a mean difference of -0.2 ± 3.82 mm, with five out of the nineteen (5/19, 26.3%) paired observations different by ± 5 mm or more. The qualitative assessment of the ECG-gated CT studies versus the echocardiograms is graphically displayed in Figure 4. The radiologist rated his assessment of the aortic root as “accurate” for all 19 ECG-gated CT studies; rated 3/19 studies as having “mild” ascending aorta motion artifact, with the remainder having none; rated 3/19 studies as having “partial effacement” of the sinotubular junction, with the remainder being preserved; and rated 2/19 studies as having “moderate” aortic valve calcification, 3/19 with “mild” calcification, and the remainder having none. In comparison, the cardiologist reading the echocardiography studies rated 3/19 as having “moderate” motion artifact, 7/19 with “mild” motion artifact, and the remainder having none; 3/19 studies showed “full effacement” of the sinotubular junction, 8/19 were “partially effaced”, and the remainder were preserved; and rated 1/19 studies as having “moderate” aortic valve calcification, 6/19 with “mild” calcification, and the remainder having none.

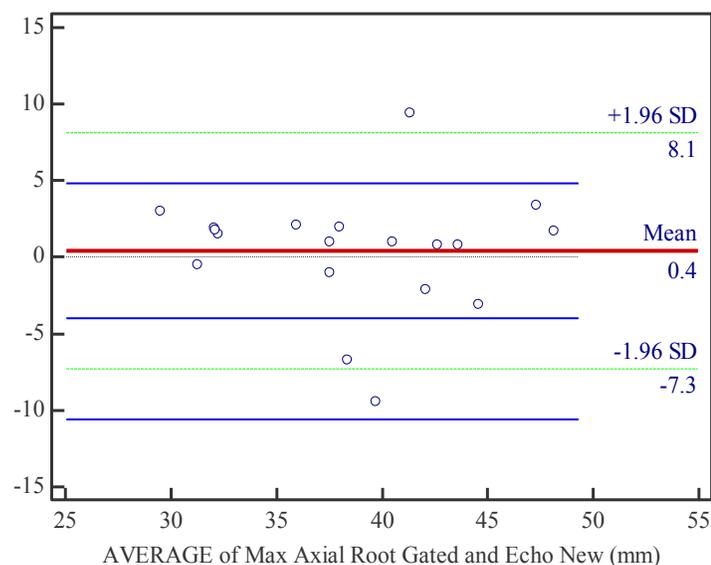


Figure 5. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the axial dimension on ECG-gated CT studies by a single radiologist (Max Axial Root Gated) and those made by a single cardiologist (Echo New) on the same patients' echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical "no difference" outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

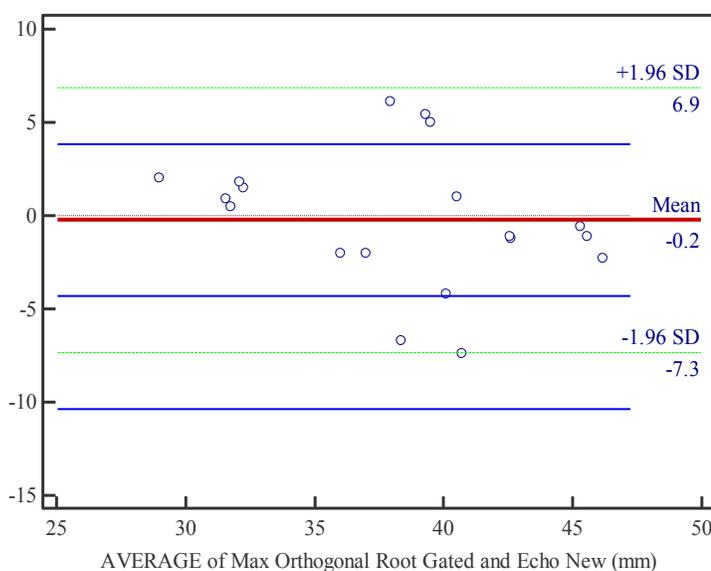


Figure 6. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the orthogonal dimension on ECG-gated CT studies by a single radiologist (Max Orthogonal Root Gated) and those made by a single cardiologist (Echo New) on the same patients' echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical "no difference" outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

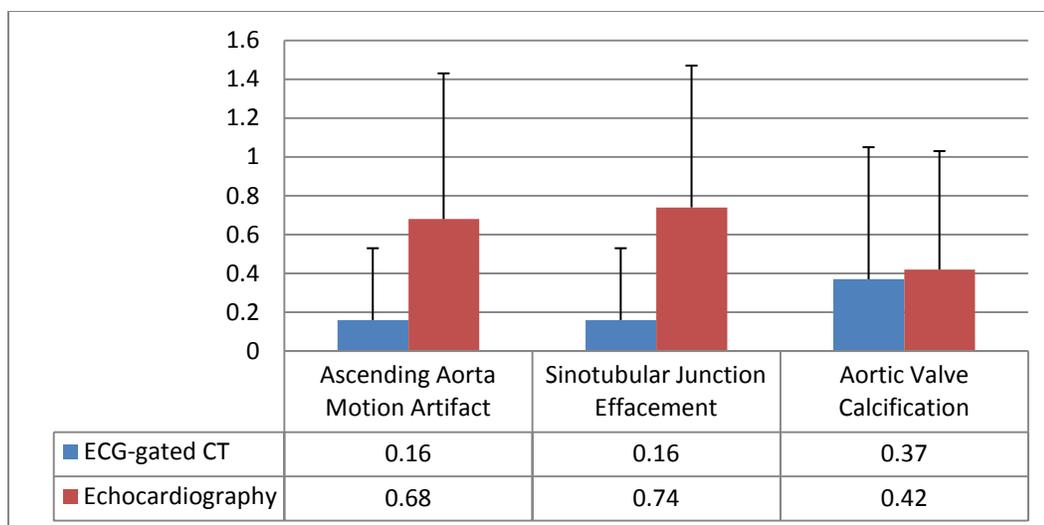


Figure 7. Qualitative assessment of ECG-gated computed tomography (CT) versus echocardiography. The technical quality of each study was assessed using the following parametric criteria: ascending aorta motion artifact was graded on a scale of 0, 1, 2, or 3, for none, mild, moderate, or severe, respectively; the image quality of the sinotubular junction was graded as 0, 1, or 2, for preserved, partially effaced, or fully effaced, respectively; the amount of aortic valve calcification, which may interfere with accurate measurement of the aortic root, was graded on a scale of 0, 1, 2, or 3, for none, mild, moderate, or severe, respectively. Plotted are the mean values with their respective positive (+) standard deviation error bars.

Aortic root measurements made in both axial and orthogonal dimensions on ECG-gated CT were compared with the measurements made on prior echocardiography measurements. For the axial dimension (Fig. 5), there was a mean difference of 2.2 ± 3.16 mm, with two out of the nineteen (2/19, 10.5%) paired observations differing by ± 5 mm or more. For the orthogonal dimension (Fig. 6), there was a mean difference of 1.5 ± 3.98 mm, with four out of the nineteen (5/19, 26.3%) paired observations different by ± 5 mm or more.

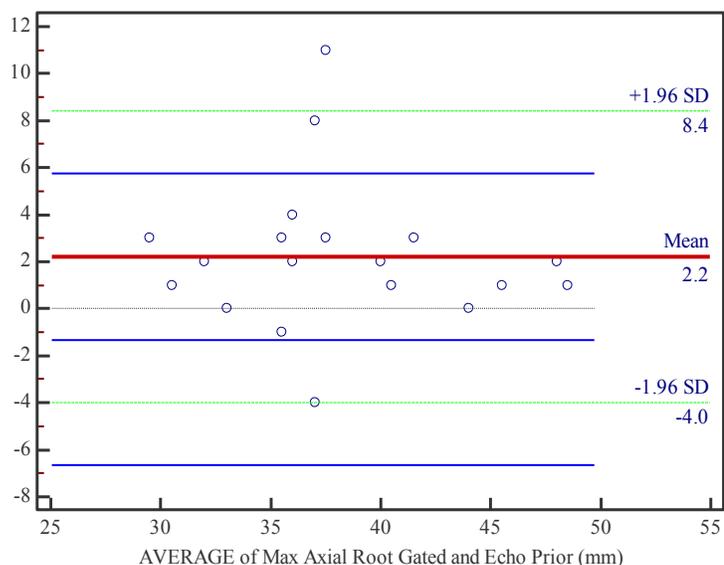


Figure 8. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the axial dimension on ECG-gated CT studies by a single radiologist (Max Axial Root Gated) and those made by multiple different cardiologists (Echo Prior) on the same patients' echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical "no difference" outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

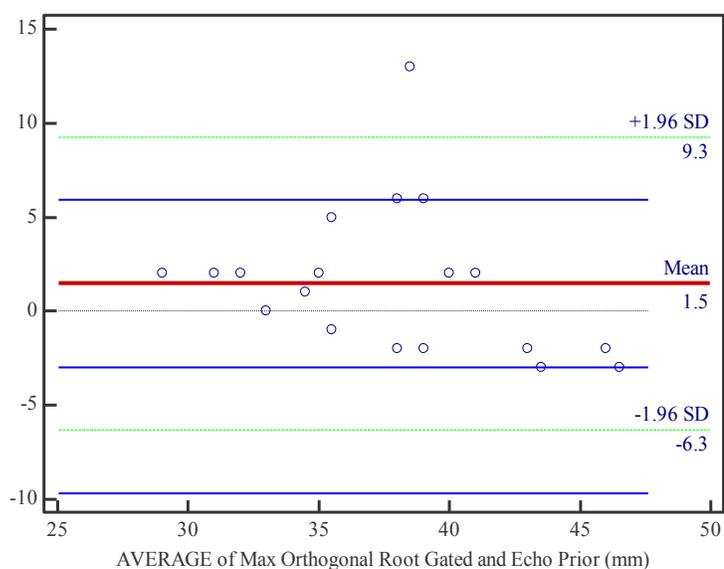


Figure 9. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the orthogonal dimension on ECG-gated CT studies by a single radiologist (Max Orthogonal Root Gated) and those made by multiple different cardiologists (Echo Prior) on the same patients' echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical "no difference" outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Prior aortic root measurements made in both axial and orthogonal dimensions on ECG-gated CT were compared with the measurements made on prior echocardiography measurements (Fig. 7). There was a mean difference of 1.9 ± 4.74 mm, with four out of the eleven (4/11, 36.3%) paired observations differing by ± 5 mm or more.

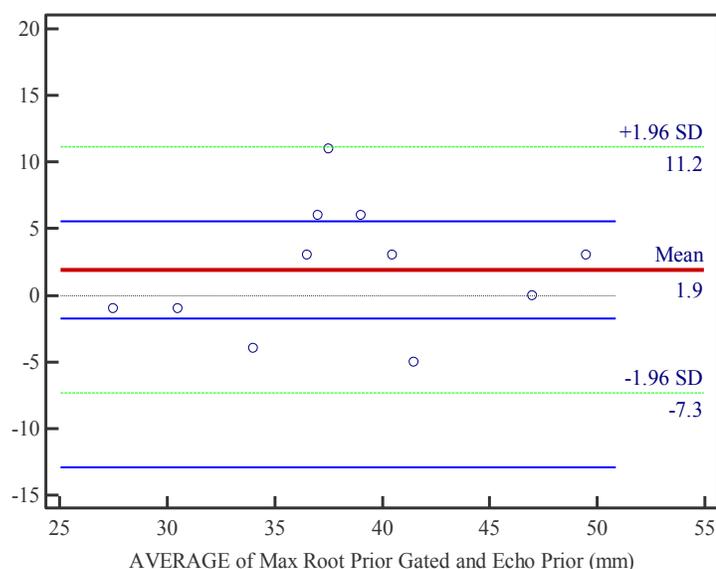


Figure 10. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made on ECG-gated CT studies by multiple different radiologists (Max Root Prior Gated) and those made by multiple different cardiologists (Echo Prior) on the same patients' echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical "no difference" outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Aortic root measurements made in both axial and orthogonal dimensions on non-ECG-gated CT were compared with the measurements made on repeat echocardiography measurements. For the axial dimension (Fig. 8), there was a mean difference of 0.9 ± 5.92 mm, with eleven out of the thirty (11/30, 36.6%) paired observations differing by ± 5 mm or more. For the orthogonal dimension (Fig. 9), there was a mean difference of 1.1 ± 5.46 mm, with ten out of the thirty (10/30, 33.3%) paired observations different by ± 5 mm or more. The qualitative assessment of the non-ECG-gated CT studies versus the

echocardiograms is graphically displayed in Figure 10. The radiologist rated his assessment of the aortic root as “accurate” for 6/30 non-ECG-gated CT studies, as “poor” for 23/30, and as “unable to measure” for 1/30; rated 14/30 studies as having “moderate” ascending aorta motion artifact, 15/30 with “mild” motion artifact, and only one with none; rated 11/30 studies as having “partial effacement” of the sinotubular junction, with the remaining 19/30 being preserved; and rated 4/30 studies as having “moderate” aortic valve calcification, 6/30 with “mild” calcification, and the remainder having none. In comparison, the cardiologist reading the echocardiography studies rated 11/30 as having “moderate” motion artifact, 10/30 with “mild” motion artifact, and the remainder having none; 11/30 studies showed “full effacement” of the sinotubular junction, 5/30 were “partially effaced”, and the remainder were preserved; and rated 2/30 studies as having “severe” aortic valve calcification, 5/30 as having “moderate” calcification, 3/30 with “mild” calcification, and the remainder having none.

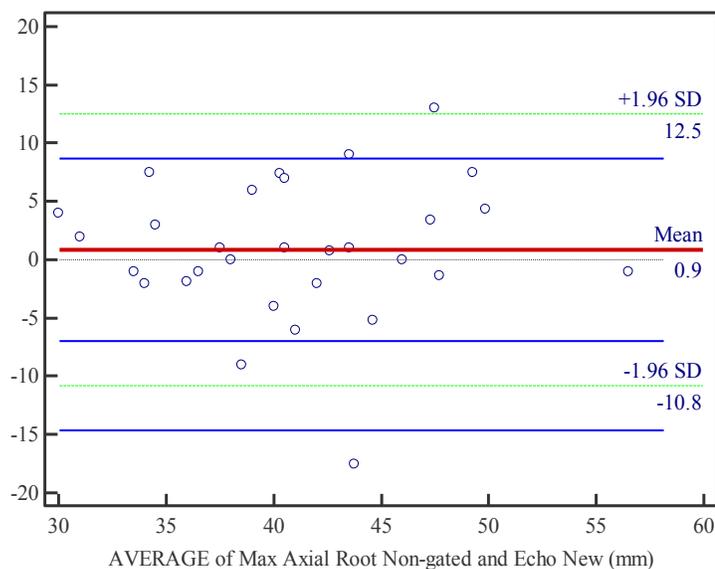


Figure 11. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the axial dimension on non-ECG-gated CT studies by a single radiologist (Max Axial Root Non-gated) and those made by a single cardiologist (Echo New) on the same patients' echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical "no difference" outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

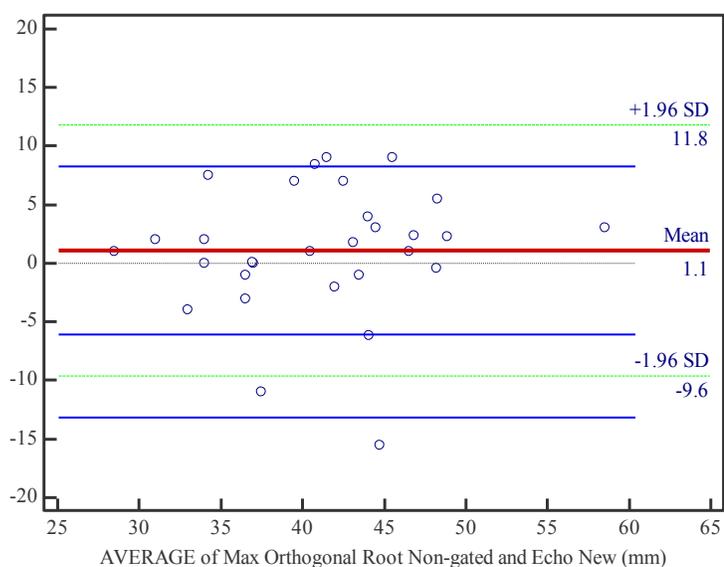


Figure 12. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the orthogonal dimension on non-ECG-gated CT studies by a single radiologist (Max Orthogonal Root Non-gated) and those made by a single cardiologist (Echo New) on the same patients' echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical "no difference" outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

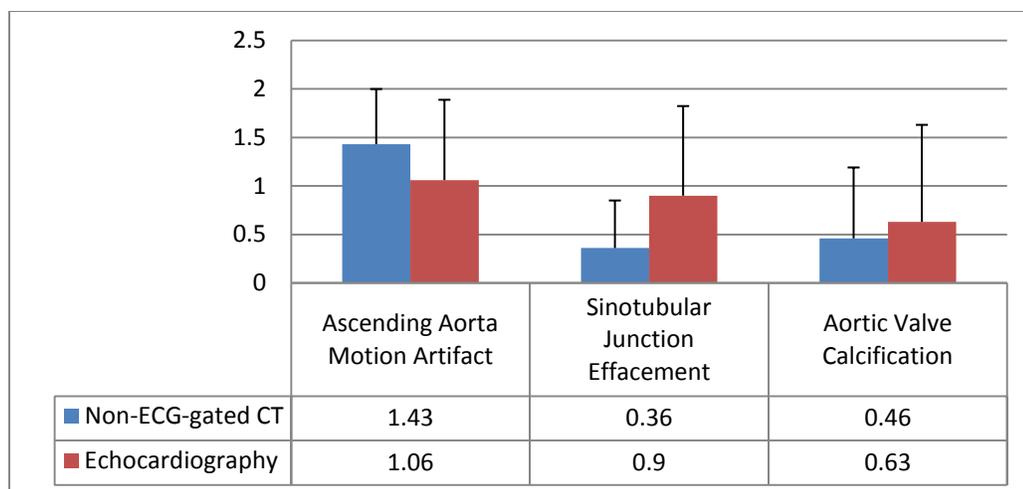


Figure 13. Qualitative assessment of non-ECG-gated computed tomography (CT) versus echocardiography. The technical quality of each study was assessed using the following parametric criteria: ascending aorta motion artifact was graded on a scale of 0, 1, 2, or 3, for none, mild, moderate, or severe, respectively; the image quality of the sinotubular junction was graded as 0, 1, or 2, for preserved, partially effaced, or fully effaced, respectively; the amount of aortic valve calcification, which may interfere with accurate measurement of the aortic root, was graded on a scale of 0, 1, 2, or 3, for none, mild, moderate, or severe, respectively. Plotted are the mean values with their respective positive (+) standard deviation error bars.

Aortic root measurements made in both axial and orthogonal dimensions on non-ECG-gated CT were compared with the measurements made on prior echocardiography measurements. For the axial dimension (Fig. 11), there was a mean difference of 3.8 ± 5.05 mm, with eight out of the thirty (8/30, 26.6%) paired observations differing by ± 5 mm or more. For the orthogonal dimension (Fig. 12), there was a mean difference of 4.0 ± 5.25 mm, with nine out of the thirty (9/30, 30.0%) paired observations different by ± 5 mm or more.

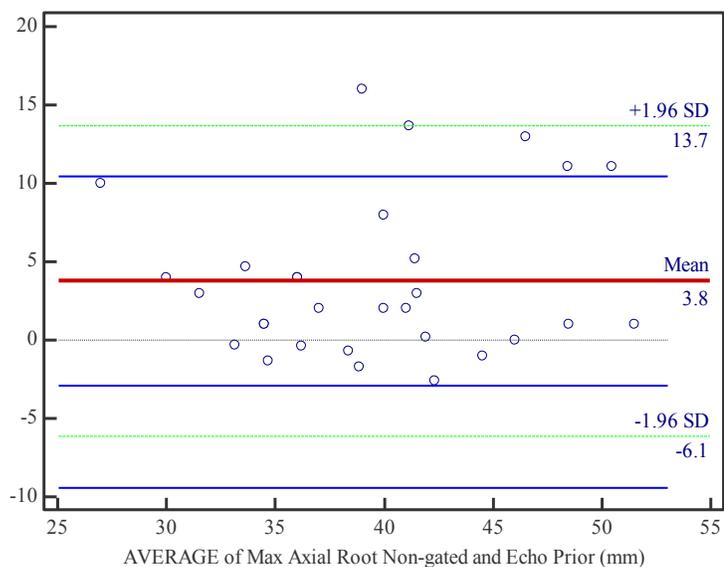


Figure 14. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the axial dimension on non-ECG-gated CT studies by a single radiologist (Max Axial Root Non-gated) and those made by multiple different cardiologists (Echo Prior) on the same patients' echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical "no difference" outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

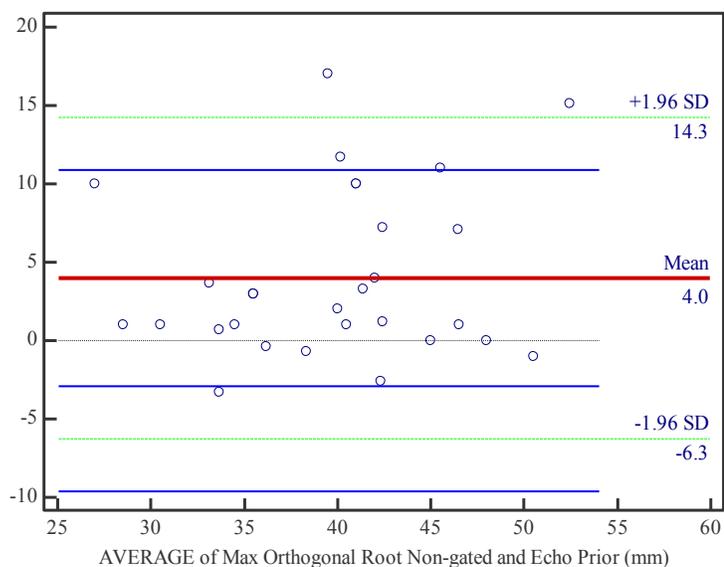


Figure 15. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the orthogonal dimension on non-ECG-gated CT studies by a single radiologist (Max Orthogonal Root Non-gated) and those made by multiple different cardiologists (Echo Prior) on the same patients' echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical "no difference" outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Prior aortic root measurements made in both axial and orthogonal dimensions on ECG-gated CT were compared with the measurements made on prior echocardiography measurements (Fig. 13). There was a mean difference of 5.2 ± 6.88 mm, with three out of the seven (3/7, 42.8%) paired observations differing by ± 5 mm or more.

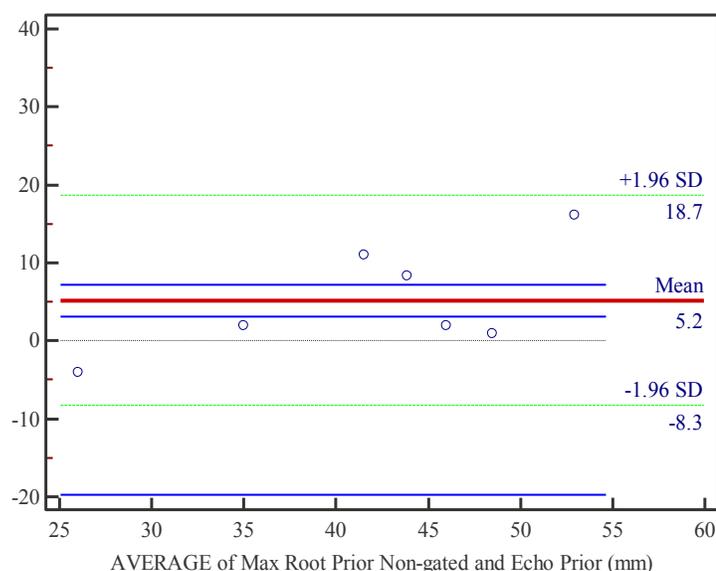


Figure 16. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made on non-ECG-gated CT studies by multiple different radiologists (Max Root Prior Non-gated) and those made by multiple different cardiologists (Echo Prior) on the same patients’ echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Aortic root measurements made in both axial and orthogonal dimensions on ECG-gated CT were compared with the measurements made on non-ECG-gated CT. For the axial dimension (Fig. 14), there was a mean difference of -0.6 ± 1.99 mm, with one out of the eight (1/8, 12.5%) paired observations differing by ± 5 mm or more. For the orthogonal dimension (Fig. 15), there was a mean difference of -2.0 ± 2.50 mm, with one out of the eight (1/8, 12.5%) paired observations differing by ± 5 mm or more. The qualitative assessment of the ECG-gated CT studies versus the non-ECG-gated CT

studies is graphically displayed in Figure 16. The radiologist rated his assessment of the aortic root as “accurate” for all 8 ECG-gated CT studies; rated 1/8 studies as having “mild” ascending aorta motion artifact, with the remainder having none; rated 3/8 studies as having “partial effacement” of the sinotubular junction, with the remainder being preserved; and rated 1/8 studies as having “moderate” aortic valve calcification, with the remainder having none. In comparison, the same radiologist rated his assessment of the aortic root as “poor” for all 8 non-ECG-gated CT studies; rated 4/8 as having “moderate” motion artifact, 3/8 with “mild” motion artifact, and only 1/8 with none; 3/8 studies showed “partial effacement” of the sinotubular junction, with the remainder being preserved; and rated 1/8 studies as having “moderate” aortic valve calcification, 1/8 with “mild” calcification, and the remainder having none.

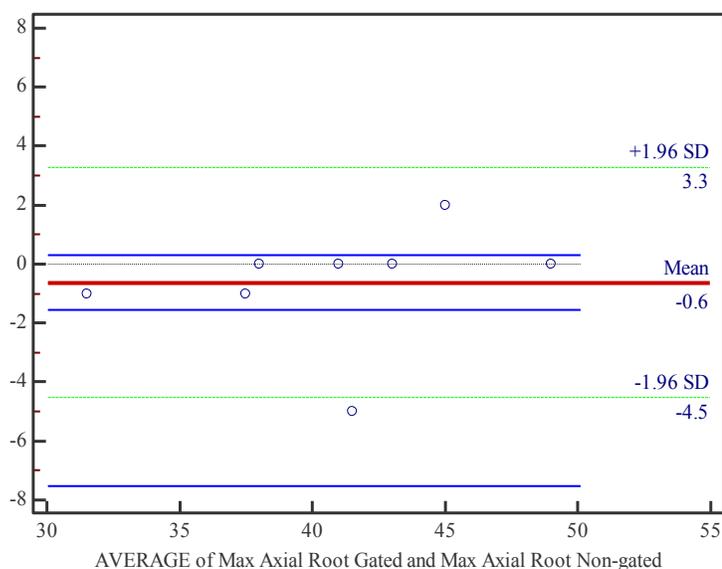


Figure 17. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the axial dimension on ECG-gated CT studies by a single radiologist (Max Axial Root Gated) and those made in the axial dimension on non-ECG-gated studies by the same radiologist (Max Axial Root Non-gated) on the same patients’ echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

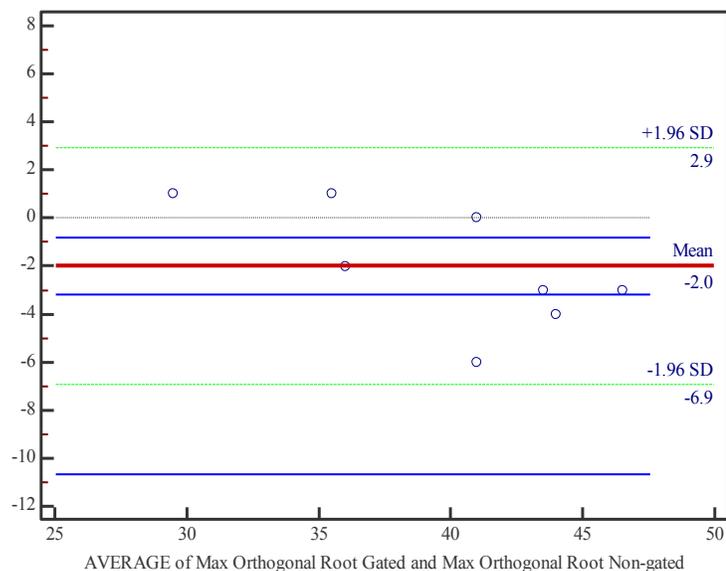


Figure 18. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the orthogonal dimension on ECG-gated CT studies by a single radiologist (Max Orthogonal Root Gated) and those made in the orthogonal dimension on non-ECG-gated studies by the same radiologist (Max Orthogonal Root Non-gated) on the same patients' echocardiograms. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical "no difference" outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

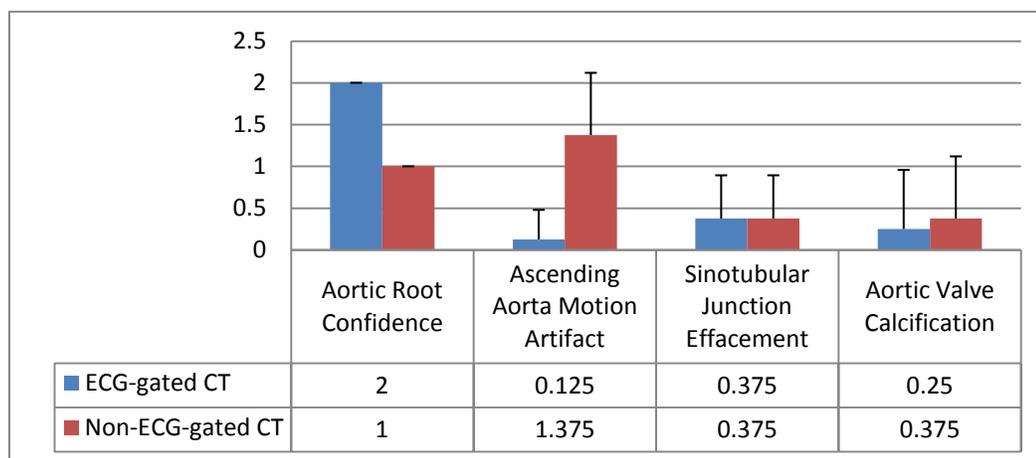


Figure 19. Qualitative assessment of ECG-gated computed tomography (CT) versus non-ECG-gated CT. The technical quality of each study was assessed using the following parametric criteria: ascending aorta motion artifact was graded on a scale of 0, 1, 2, or 3, for none, mild, moderate, or severe, respectively; the image quality of the sinotubular junction was graded as 0, 1, or 2, for preserved, partially effaced, or fully effaced, respectively; the amount of aortic valve calcification, which may interfere with accurate measurement of the aortic root, was graded on a scale of 0, 1, 2, or 3, for none, mild, moderate, or severe, respectively. Plotted are the mean values with their respective positive (+) standard deviation error bars.

Measurements of the sinotubular junction made in both axial and orthogonal dimensions on ECG-gated CT were compared with the measurements made on non-ECG-gated CT. For the axial dimension (Fig. 17), there was a mean difference of -1.1 ± 2.09 mm, with none out of the eight (0/8, 0%) paired observations differing by ± 5 mm or more. For the orthogonal dimension (Fig. 18), there was a mean difference of -0.6 ± 3.57 mm, with three out of the eight (3/8, 37.5%) paired observations differing by ± 5 mm or more.

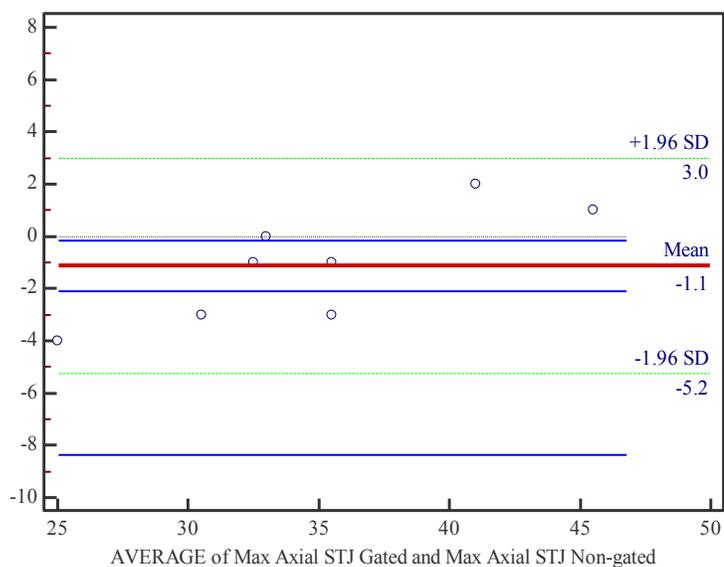


Figure 20. Bland-Altman plot displaying the mean difference (bias) between sinotubular junction (STJ) measurements made in the axial dimension on ECG-gated CT studies by a single radiologist (Max Axial STJ Gated) and those made by the same radiologist in the axial dimension on non-ECG-gated studies (Max Axial STJ Non-gated) performed on the same set of patients. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

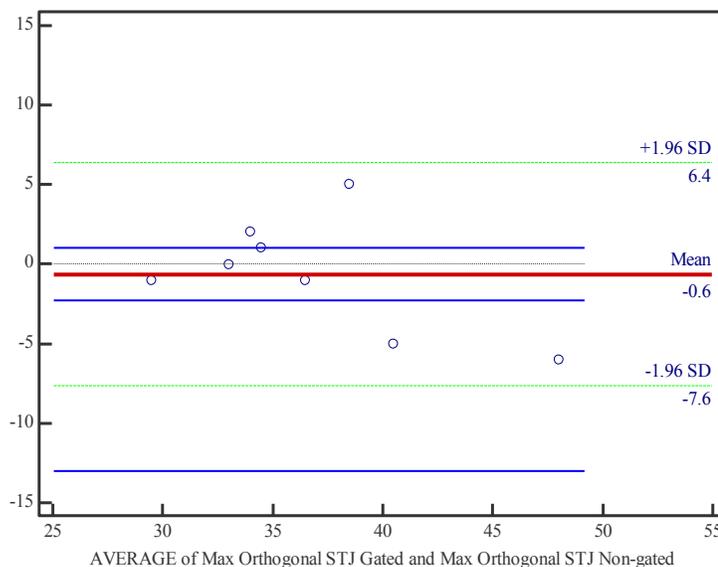


Figure 21. Bland-Altman plot displaying the mean difference (bias) between sinotubular junction (STJ) measurements made in the orthogonal dimension on ECG-gated CT studies by a single radiologist (Max Orthogonal STJ Gated) and those made by the same radiologist in the orthogonal dimension on non-ECG-gated studies (Max Orthogonal STJ Non-gated) performed on the same set of patients. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Measurements of the maximum ascending aorta made in both axial and orthogonal dimensions on ECG-gated CT were compared with the measurements made on non-ECG-gated CT. For the axial dimension (Fig. 19), there was a mean difference of -0.1 ± 3.67 mm, with one out of the eight (1/8, 12.5%) paired observations differing by ± 5 mm or more. For the orthogonal dimension (Fig. 20), there was a mean difference of -1.3 ± 2.75 mm, with one out of the eight (1/8, 12.5%) paired observations differing by ± 5 mm or more.

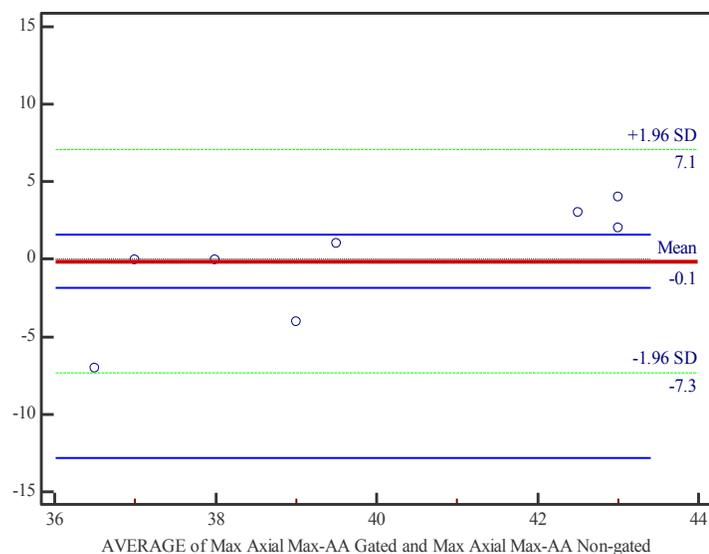


Figure 22. Bland-Altman plot displaying the mean difference (bias) between maximum ascending aorta (Max-AA) measurements made in the axial dimension on ECG-gated CT studies by a single radiologist (Max Axial Max-AA Gated) and those made by the same radiologist in the axial dimension on non-ECG-gated studies (Max Axial Max-AA Non-gated) performed on the same set of patients. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

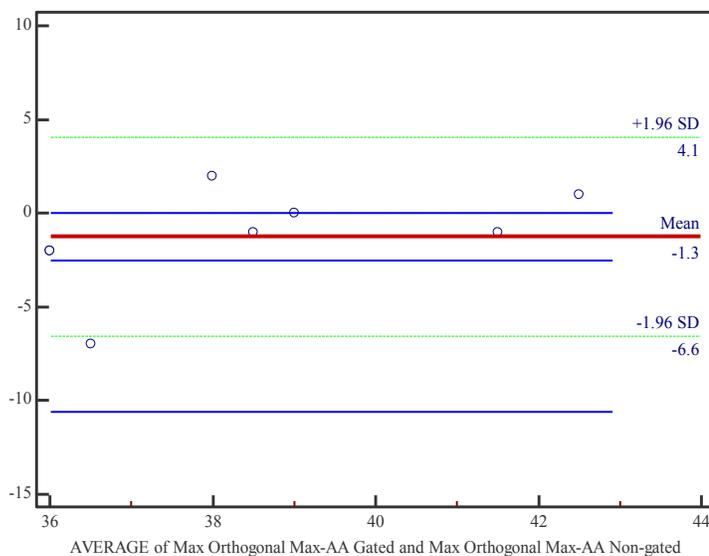


Figure 23. Bland-Altman plot displaying the mean difference (bias) between maximum ascending aorta (Max-AA) measurements made in the orthogonal dimension on ECG-gated CT studies by a single radiologist (Max Orthogonal Max-AA Gated) and those made by the same radiologist in the orthogonal dimension on non-ECG-gated studies (Max Orthogonal Max-AA Non-gated) performed on the same set of patients. The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Comparison of prior and repeat measurements of the aortic root, sinotubular junction, and maximum ascending aorta on both ECG-gated CT and non-ECG-gated CT was limited by the deficient and inconsistent reporting of measurement data by radiologists dictating prior CT reports (Table 1). Of the twenty-one ECG-gated CT studies included in this study, only twelve reported measurements of the aortic root, twelve of the sinotubular junction, and nine of the maximum ascending aorta. Nine of the twenty-one studies included measurements at the level of the sinuses of Valsalva, but the reports did not specify if this was to be interpreted as the “aortic root”. Five of the twenty-one studies included measurements of the proximal ascending aorta and nine of the mid-ascending aorta, but none of the reports provided any definitive anatomic landmarks to clarify the meaning of the terms “proximal” and “mid” for the referring clinician. Three of the 21 ECG-gated CT studies included no aortic measurements at all.

CT Study Type	Protocol			Root	Sinuses	STJ	Proximal Asc Aorta	Mid Asc Aorta	Max Asc Aorta	Just Asc Aorta	No measurements at all
	CTA Chest/Abd Dissection	CT Angio Chest	CT Scan Chest w/wo Contrast								
ECG-gated				12	9	12	5	9	9	0	3
	5	16	0								
Non-ECG-gated				7	2	1	2	5	6	5	12
	14	6	10								

Table 1. Relative rates of radiologists’ reporting of various aortic measurements broken down by type of computed tomography (CT) study ordered by referring clinicians.

Of the thirty non-ECG-gated CT studies included in this study, only seven reported measurements of the aortic root, one of the sinotubular junction, and six of the maximum ascending aorta. Two of the thirty studies included measurements at the level of the sinuses of Valsalva, but the reports did not specify if this was to be interpreted as the “aortic root”. Two of the thirty studies included measurements of the proximal ascending aorta and five of the mid-ascending aorta, but none of the reports provided any definitive anatomic landmarks to clarify the meaning of the terms “proximal” and “mid” for the referring clinician. Twelve of the thirty non-ECG-gated CT studies included no aortic measurements at all.

Comparison of prior and repeat measurements of the aortic root made via ECG-gated CT revealed a mean difference of 0.3 ± 3.06 mm in the axial dimension (Fig. 21), with two of the twelve (2/12, 16.6%) paired observations differing by ± 5 mm or more, and a mean difference of 0.3 ± 3.26 mm in the orthogonal dimension (Fig. 22), with two of the twelve (2/12, 16.6%) paired observations differing by ± 5 mm or more.

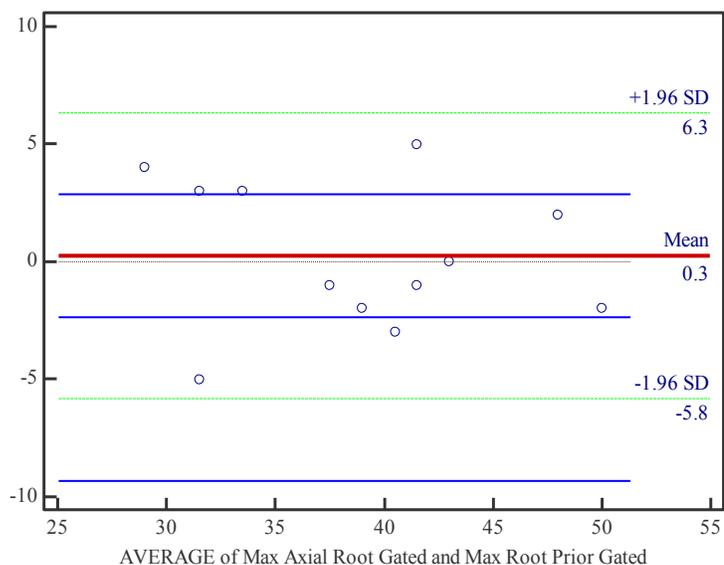


Figure 24. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the axial dimension on ECG-gated CT studies by a single radiologist (Max Axial Root Gated) and those made on the same ECG-gated CT studies by multiple different radiologists (Max Root Prior Gated). The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

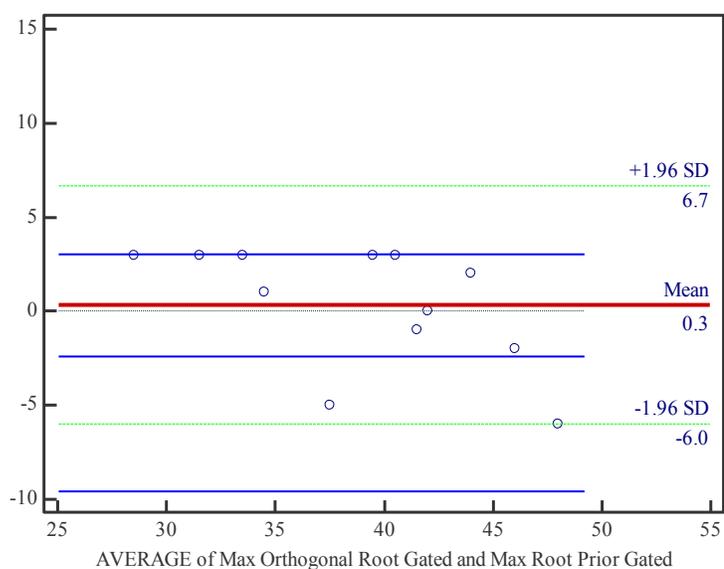


Figure 25. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the orthogonal dimension on ECG-gated CT studies by a single radiologist (Max Orthogonal Root Gated) and those made on the same ECG-gated CT studies by multiple different radiologists (Max Root Prior Gated). The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Comparison of prior and repeat measurements of the aortic root made via non-ECG-gated CT revealed a mean difference of -2.4 ± 6.32 mm in the axial dimension (Fig. 23), with four of the seven (4/7, 57.1%) paired observations differing by ± 5 mm or more, and a mean difference of -0.6 ± 3.01 mm in the orthogonal dimension (Fig. 24), with two of the seven (2/7, 28.5%) paired observations differing by ± 5 mm or more.

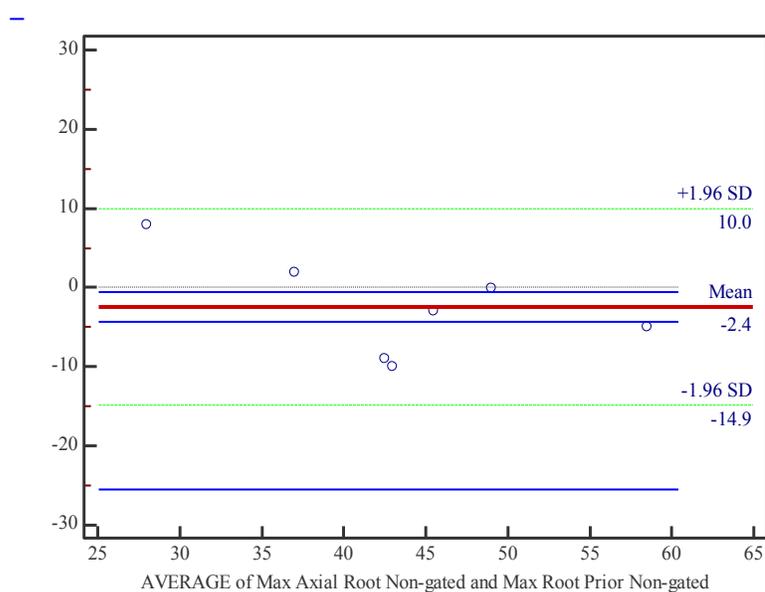


Figure 26. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the axial dimension on non-ECG-gated CT studies by a single radiologist (Max Axial Root Non-gated) and those made on the same non-ECG-gated CT studies by multiple different radiologists (Max Root Prior Non-gated). The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

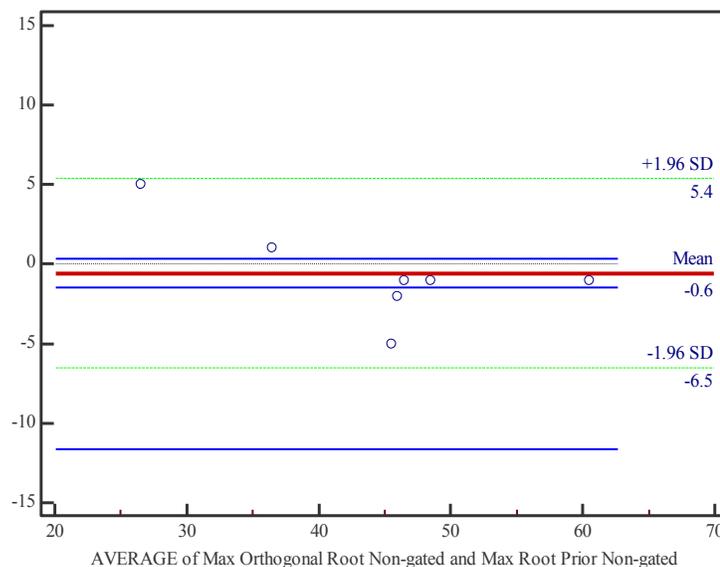


Figure 27. Bland-Altman plot displaying the mean difference (bias) between aortic root measurements made in the orthogonal dimension on non-ECG-gated CT studies by a single radiologist (Max Orthogonal Root Non-gated) and those made on the same non-ECG-gated CT studies by multiple different radiologists (Max Root Prior Non-gated). The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Comparison of prior and repeat measurements of the sinotubular junction made via ECG-gated CT revealed a mean difference of -3.2 ± 3.06 mm in the axial dimension (Fig. 25), with two of the twelve (2/12, 16.6%) paired observations differing by ± 5 mm or more, and a mean difference of -0.2 ± 1.88 mm in the orthogonal dimension (Fig. 26), with one of the twelve (1/12, 8.3%) paired observations differing by ± 5 mm or more.

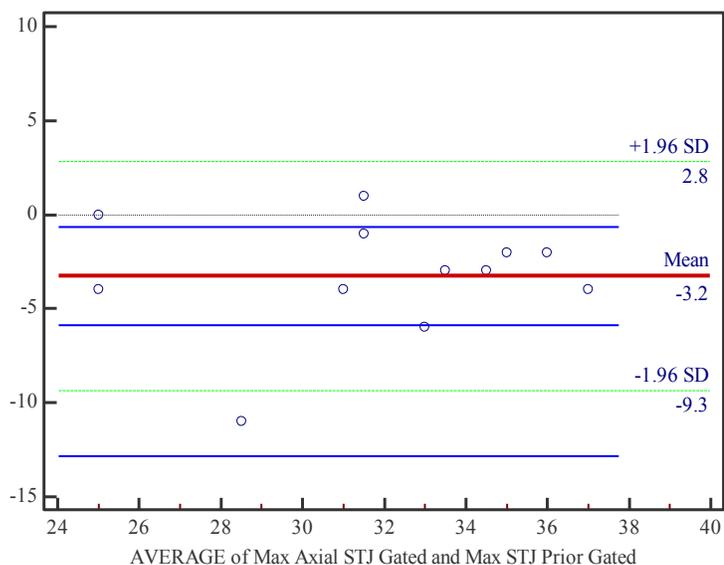


Figure 28. Bland-Altman plot displaying the mean difference (bias) between sinotubular junction (STJ) measurements made in the axial dimension on ECG-gated CT studies by a single radiologist (Max Axial STJ Gated) and those made on the same ECG-gated CT studies by multiple different radiologists (Max STJ Prior Gated). The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

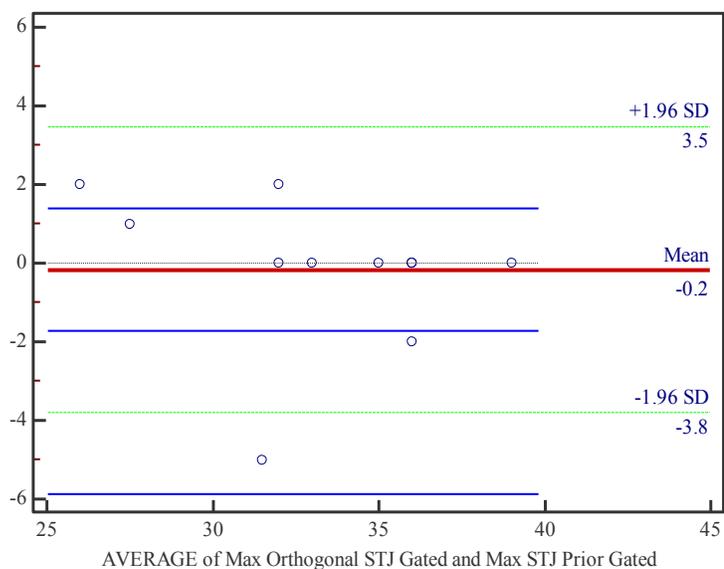


Figure 29. Bland-Altman plot displaying the mean difference (bias) between sinotubular junction (STJ) measurements made in the orthogonal dimension on ECG-gated CT studies by a single radiologist (Max Orthogonal STJ Gated) and those made on the same ECG-gated CT studies by multiple different radiologists (Max STJ Prior Gated). The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Comparison of prior and repeat measurements of the sinotubular junction made via non-ECG-gated CT was not possible due to an insufficient number of paired observations available for Bland-Altman plot analysis.

Comparison of prior and repeat measurements of the maximum ascending aorta made via ECG-gated CT revealed a mean difference of 2.9 ± 4.69 mm in the axial dimension (Fig. 27), with two of the nine (2/9, 22.2%) paired observations differing by ± 5 mm or more, and a mean difference of 1.1 ± 4.18 mm in the orthogonal dimension (Fig. 28), with one of the nine (1/9, 11.1%) paired observations differing by ± 5 mm or more.

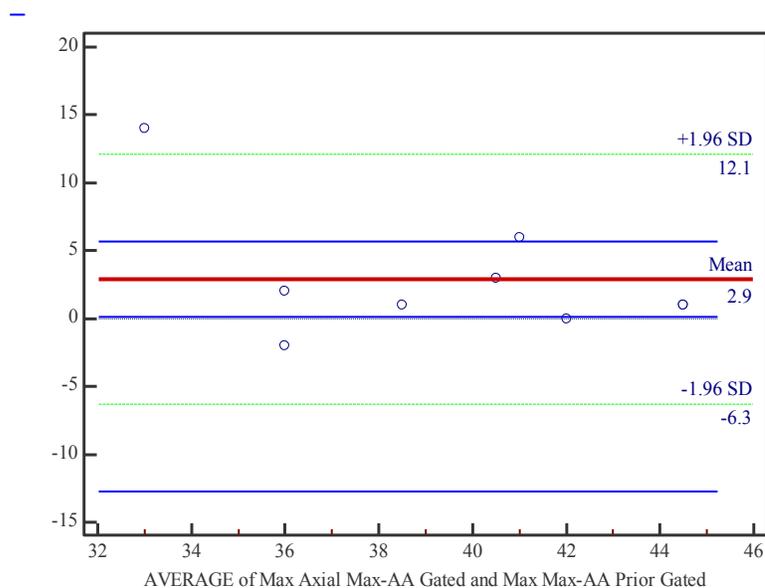


Figure 30. Bland-Altman plot displaying the mean difference (bias) between maximum ascending aorta (Max-AA) measurements made in the axial dimension on ECG-gated CT studies by a single radiologist (Max Axial Max-AA Gated) and those made on the same ECG-gated CT studies by multiple different radiologists (Max Max-AA Prior Gated). The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

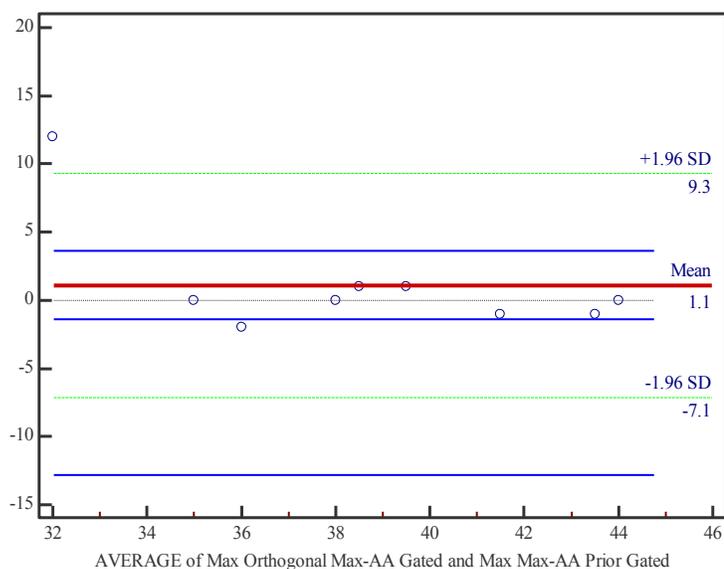


Figure 31. Bland-Altman plot displaying the mean difference (bias) between maximum ascending aorta (Max-AA) measurements made in the orthogonal dimension on ECG-gated CT studies by a single radiologist (Max Orthogonal Max-AA Gated) and those made on the same ECG-gated CT studies by multiple different radiologists (Max Max-AA Prior Gated). The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Comparison of prior and repeat measurements of the maximum ascending aorta made via non-ECG-gated CT revealed a mean difference of 2.5 ± 8.31 mm in the axial dimension (Fig. 29), with three of the six (3/6, 50.0%) paired observations differing by ± 5 mm or more, and a mean difference of -0.5 ± 5.46 mm in the orthogonal dimension (Fig. 30), with one of the six (1/6, 16.6%) paired observations differing by ± 5 mm or more.

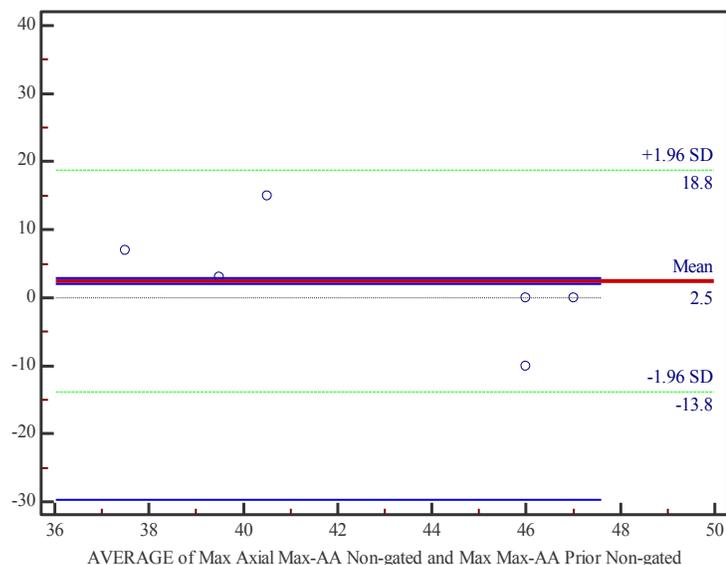


Figure 32. Bland-Altman plot displaying the mean difference (bias) between maximum ascending aorta (Max-AA) measurements made in the axial dimension on non-ECG-gated CT studies by a single radiologist (Max Axial Max-AA Non-gated) and those made on the same non-ECG-gated CT studies by multiple different radiologists (Max Max-AA Prior Non-gated). The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

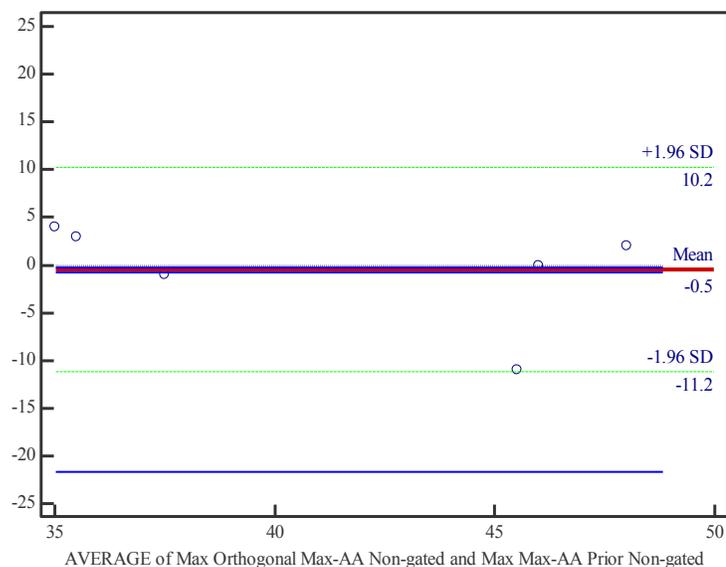


Figure 33. Bland-Altman plot displaying the mean difference (bias) between maximum ascending aorta (Max-AA) measurements made in the orthogonal dimension on non-ECG-gated CT studies by a single radiologist (Max Orthogonal Max-AA Non-gated) and those made on the same non-ECG-gated CT studies by multiple different radiologists (Max Max-AA Prior Non-gated). The red line represents the mean difference; the dotted black line set at zero (0) represents the hypothetical “no difference” outcome; the hashed green lines flanked by solid blue lines represent the limits of agreement and their associated 95% confidence intervals.

Discussion

The results obtained from this comparison study of multiple imaging modalities reveal a number of important findings that should guide future radiological examination of the aortic root. The first conclusion that can be drawn is that inter-cardiologist measurements of the aortic root performed on echocardiography lack reproducibility, as the mean of differences between repeat measurements on the same patients' studies was large at a value of 2.9 mm, with a large standard deviation of 5.76 mm. Cardiothoracic surgeons consider a change of 5 mm to be a clinically significant progression, and there was approximately a 37.5% chance that any patient whose echocardiogram was read by two different cardiologists would have a ± 5 mm difference reported in the size of their aortic root. Should this measurement error cause a patient's aortic root size to reach or exceed the critical 5 cm point, the impact on clinical decision making is substantial, with the patient either being sent for open thoracotomy and surgical valve replacement versus not. It is likely that this variation aortic root measurements stems from the inherently poor image quality of echocardiography, which is subject to significant motion artifact that, in turn, significantly compromises image spatial resolution. This is reflected by the study quality measurements reported by the cardiologist reviewing the echocardiograms—27/40 studies were rated as having moderate or mild motion artifact, and 24/40 studies showed full or partial effacement of the sinotubular junction, making precise identification of anatomic landmarks difficult. These results of large measurement variation speak against the use of echocardiography for serial follow-up of aortic root pathologies.

Aortic root measurements obtained via ECG-gated CT showed better agreement with repeat echocardiographic measurements than did those obtained via non-ECG-gated CT. The mean measurement differences between ECG-gated CT and echocardiography in the axial and orthogonal dimensions (0.4 mm and -0.2 mm, respectively) were smaller than those between non-ECG-gated CT and echocardiography (0.9 mm and 1.1 mm, respectively). More importantly, the standard deviations of the measurement differences between ECG-gated CT and echocardiography in the axial and orthogonal dimensions (3.93 mm and 3.82 mm, respectively) were smaller than those between non-ECG-gated CT and echocardiography (5.92 mm and 5.46 mm, respectively). For the axial dimension, 15.7% of ECG-gated CT measurements differed with the echocardiography measurements by ± 5 mm or more, compared with 36.6% of non-ECG-gated CT measurements. For the orthogonal dimension, 26.3% of ECG-gated CT measurements differed with the echocardiography measurements by ± 5 mm or more, compared with 33.3% of non-ECG-gated CT measurements. Significantly less motion artifact and better preservation of the sinotubular junction was noted between ECG-gated CT and echocardiography than between non-ECG-gated CT and echocardiography.

Comparison of aortic root measurements made by a single radiologist reading ECG-gated CT studies with prior echocardiographic measurements made by multiple different cardiologists showed a larger mean difference and an approximately equally large standard deviation than the comparison with repeat echocardiographic measurements made by a single cardiologist (2.2 ± 3.16 mm in the axial dimension and 1.5 ± 3.98 mm in the orthogonal dimension versus 0.4 ± 3.93 mm in the axial dimension and -0.2 ± 3.82 mm in the orthogonal dimension). Comparison of prior aortic root

measurements made by multiple radiologists reading ECG-gated CT studies with prior echocardiographic measurements made by multiple different cardiologists showed a large mean difference (1.9 mm) and an even larger standard deviation (± 4.74 mm) than the two previous comparisons. What this suggests is that when multiple radiologists and/or cardiologists make measurements of the aortic root on CT or echocardiography, respectively, they each employ slightly different methodology that introduces bias (in the form of mean difference) and variation (in the form of standard deviation) into the measurement values.

Comparison of aortic root measurements made by a single radiologist reading non-ECG-gated CT studies with prior echocardiographic measurements made by multiple different cardiologists showed a larger mean difference and approximately equally large standard deviation than the comparison with repeat echocardiographic measurements made by a single cardiologist (3.8 ± 5.05 mm in the axial dimension and 4.0 ± 5.25 mm in the orthogonal dimension versus 0.9 ± 5.92 mm in the axial dimension and 1.1 ± 5.46 mm in the orthogonal dimension). Comparison of prior aortic root measurements made by multiple radiologists reading non-ECG-gated CT studies with prior echocardiographic measurements made by multiple different cardiologists showed a much larger mean difference (5.2 mm) and a much larger standard deviation (± 6.88 mm) than the two previous comparisons. As above, this suggests that when multiple radiologists and/or cardiologists make measurements of the aortic root on CT or echocardiography, respectively, they each employ slightly different methodology that introduces bias (in the form of mean difference) and variation (in the form of standard deviation) into the measurement values. ECG-gating, however, tends to buffer the magnitude of increase in

mean difference and standard deviation due to multiple readers when compared to non-ECG-gated CT studies.

When the same radiologist applied the same method of measurement of the aortic root, there was good agreement between the measurement values obtained via ECG-gated CT and non-ECG-gated CT in the axial dimension, with a mean difference of -0.6 ± 1.99 mm and only 12.5% of values differing by ± 5 mm or more. For reasons unclear, there is a small bias in the measurement of the aortic root in the orthogonal dimension when comparing ECG-gated CT with non-ECG-gated CT, with a mean difference of -2.0 ± 2.50 mm, but only one out of the eight (1/8, 12.5%) paired observations differing by ± 5 mm or more.

When two different radiologists employed two different methods of measurement of the aortic root, there was a much greater increase in mean difference and standard deviation in axial aortic root size for non-ECG-gated CT as compared with ECG-gated CT. Prior and repeat measurements of the aortic root on non-ECG-gated CT produced a mean difference of -2.4 ± 6.32 mm in the axial dimension, with four of the seven (4/7, 57.1%) paired observations differing by ± 5 mm or more. Prior and repeat measurements of the aortic root on ECG-gated CT produced a comparatively smaller mean difference of 0.3 ± 3.06 mm in the axial dimension, with only two of the twelve (2/12, 16.6%) paired observations differing by ± 5 mm or more. Prior and repeat measurements of the aortic root in the orthogonal dimension were in good agreement for both ECG-gated CT (mean difference of 0.3 ± 3.26 mm) and non-ECG-gated CT (-0.6 ± 3.01 mm). These findings suggest that when a single radiologist is employing a uniform method of axial aortic root measurement, only a small difference exists between ECG-gated and non-ECG-gated CT

studies. However, ECG-gating acts as a buffer to minimize the amount of bias and variation in aortic root measurement values that are inevitably introduced by inter-radiologist differences in measurement methods.

Evaluation of the ascending aorta for its maximum diameter is of prime importance for the referring clinician, as the size and rate of change of an ascending aortic aneurysm are important determinants of when to intervene, either via endovascular stent-grafting or open surgical repair. The results of this study show that measurements of the maximum ascending aorta made via ECG-gated CT and non-ECG-gated CT generally agree with low intra-radiologist variability, with mean differences of -0.1 ± 3.67 mm and -1.3 ± 2.75 mm in the axial and orthogonal dimensions, respectively. However, when prior and repeat measurements of the maximum ascending aorta are made by different radiologists, significant variation is introduced. The mean differences in prior and repeat measurements of the maximum ascending aorta made via ECG-gated CT were 2.9 ± 4.69 mm in the axial dimension and 1.1 ± 4.18 mm in the orthogonal dimension. The mean differences in prior and repeat measurements of the maximum ascending aorta made via non-ECG-gated CT were 2.5 ± 8.31 mm in the axial dimension and -0.5 ± 5.46 mm in the orthogonal dimension. The axial dimension had a bias of 2.9 and 2.5 mm for both CT modalities. As expected, non-ECG-gated CT had larger standard deviations in the mean difference in comparison to ECG-gated CT. This suggests that repeated follow-up of the ascending aorta for changes in its maximum diameter should be performed via ECG-gated CT and orthogonal reformatted images used for measurement.

A number of conclusions and recommendations can be made from the results of this study. In short, the results of this study demonstrate that the vast majority of bias and

variation in aortic root measurements among various imaging modalities is due much more to the lack of standard and uniform methods of measurement among cardiologists and radiologists rather than to intrinsic features or limitations of the modalities themselves. Because echocardiography is the most cost-effective and safest imaging modality, it will likely continue to be the initial study ordered in the clinical work-up of any structural aortic pathology. However, as the results of this study demonstrate, the significant amount of variation in aortic root measurement from one cardiologist reader to the next makes echocardiography an unreliable study to make critical clinical decisions upon. As such, it is recommended by the authors of this study, that any echocardiography study that produces an aortic root measurement above 3.5 cm or an ascending aorta measurement above 4.0 cm be followed soon thereafter by an ECG-gated CT study for precise measurement confirmation and superior three-dimensional characterization. The need for ECG-gated CT stems directly from the non-standard and highly non-uniform aortic measurement methods employed by different radiologists, which are the most significant source of measurement bias and variation and are only magnified by the substantial motion artifact inherent to non-ECG-gated CT. In addition, variation between CT image acquisition protocols also likely contributed to variation in image quality and, in turn, aortic root measurement confidence and accuracy. Because the results of this study demonstrate that measurements made on ECG-gated and non-ECG-gated CT agree reasonably well when the same radiologist is reading the studies, the use of non-ECG-gated CT could be recommended if serious efforts are made to standardize three important variables: CT image acquisition protocols, the list of aortic structures that should be routinely measured in every report, and the technical methods by which these

structures should be measured by radiologists. The use of non-ECG-gated CT, with its substantially lower radiation dose than its ECG-gated counterpart, would be welcomed by patients, referring clinicians, radiologists, and health policymakers alike in this age in which patient exposure to unnecessary radiation has come under intense national scrutiny.

The results of this study demonstrate that wide variation exists in which aortic structures are measured, if they are even measured or mentioned in CT reports at all. Each radiologist should include in their CT reports the technical details of the method by which they made their measurements along with still images showing the exact anatomic structures that were measured; the same practice should be adopted by cardiologists with their echocardiography reports. These images should always be made available to the referring clinician or surgeon on the hospital PACS, so as to provide them with valuable information that does not encourage them to redundantly and inaccurately repeat the measurements for “confirmation”. On an institution-wide level, effort should be made to have the same cardiologist and/or radiologist read the same patient’s follow-up echocardiography and/or CT studies, respectively. This practice would improve professional communication and relationships between radiologists and referring clinicians, and it would even foster a more meaningful doctor-patient relationship between radiologists and patients. If radiologists consulted in person with patients to review the results of their studies, the visibility of radiology as a medical subspecialty among patients would increase and patient care would only benefit. Finally, if radiologists expect to play a role in the future development and clinical use of image-guided interventional techniques, such as thoracic endovascular aneurysm repair

(TEVAR) or transcatheter aortic valve implantation (TAVI), their image interpretation skills across multiple imaging modalities must remain superior and add value to the team of cardiologists, cardiothoracic surgeons, and vascular surgeons working in these overlapping clinical spheres. By developing and adhering to rigorous and uniform standards of aortic measurement, radiologists will play a central role in the success of these minimally invasive interventional procedures.

References

1. Ocak, I., Lacomis, J.M., Deible, C.R., Pealer, K., Parag, Y., and Knollmann, F. 2009. The aortic root: comparison of measurements from ECG-gated CT angiography with transthoracic echocardiography. *J. Thorac. Imaging* **24**:223-226.
2. del Valle-Fernandez, R., Jelnin, V., Panagopoulos, G., Dudi, Y., Schneider, L., de Jaegere, P.T., Schultz, C., Serruys, P.W., Grube, E., and Ruiz, C.E. 2010. A method for standardized computed tomography angiography-based measurement of aortic valvar structures. *Eur. Heart J.* **31**:2170-2178; Epub 2010 May 25.
3. Alegret, J.M., Calvo, N., Liger, C., Palomares, R., Milla, L., Martin-Paredero, V., Montero, M., and Joven, J. 2010. Dilated aortic root is related to a global aortic dilating diathesis. *J. Vasc. Surg.* **52**:867-871.
4. Elefteriades, J.A., and Farkas, E.A. 2010. Thoracic aortic aneurysm clinically pertinent controversies and uncertainties. *J. Am. Coll. Cardiol.* **55**:841-857.
5. National Center for Injury Prevention and Control. WISQARS Leading Causes of Death Reports, 1999-2007. **2011**.
6. Delgado, V., and Bax, J.J. 2009. Classical methods to measure aortic valve area in the era of new invasive therapies: still accurate enough? *Int J Cardiovasc Imaging.* **25**:183-185; Epub 2008 Sep 18.
7. Shah, R.G., Novaro, G.M., Blandon, R.J., Whiteman, M.S., Asher, C.R., and Kirsch, J. 2009. Aortic valve area: meta-analysis of diagnostic performance of multi-detector computed tomography for aortic valve area measurements as compared to transthoracic echocardiography. *Int J Cardiovasc Imaging.* **25**:601-609; Epub 2009 May 7.
8. Bonow, R.O., Carabello, B.A., Chatterjee, K., de Leon, A.C., Jr., Faxon, D.P., Freed, M.D., Gaasch, W.H., Lytle, B.W., Nishimura, R.A., O'Gara, P.T. et al. 2008. 2008 Focused update incorporated into the ACC/AHA 2006 guidelines for the management of patients with valvular heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Writing Committee to Revise the 1998 Guidelines for the Management of Patients With Valvular Heart Disease): endorsed by the Society of Cardiovascular Anesthesiologists, Society for Cardiovascular Angiography and Interventions, and Society of Thoracic Surgeons. *Circulation* **118**:e523-661; Epub 2008 Sep 26.
9. Schlosser, F.J., Mojibian, H.R., Dardik, A., Verhagen, H.J., Moll, F.L., and Muhs, B.E. 2008. Simultaneous sizing and preoperative risk stratification for thoracic endovascular aneurysm repair: role of gated computed tomography. *J. Vasc. Surg.* **48**:561-570; Epub 2008 Jun 30.

10. Rousseau, H., Chabbert, V., Maracher, M.A., El Aassar, O., Auriol, J., Massabuau, P., and Moreno, R. 2009. The importance of imaging assessment before endovascular repair of thoracic aorta. *Eur. J. Vasc. Endovasc. Surg.* **38**:408-421; Epub 2009 Aug 4.
11. Manghat, N.E., Rachapalli, V., Van Lingen, R., Veitch, A.M., Roobottom, C.A., and Morgan-Hughes, G.J. 2008. Imaging the heart valves using ECG-gated 64-detector row cardiac CT. *Br. J. Radiol.* **81**:275-290.
12. Sahn, D.J., DeMaria, A., Kisslo, J., and Weyman, A. 1978. Recommendations regarding quantitation in M-mode echocardiography: results of a survey of echocardiographic measurements. *Circulation* **58**:1072-1083.
13. Vasan, R.S., Larson, M.G., and Levy, D. 1995. Determinants of echocardiographic aortic root size. The Framingham Heart Study. *Circulation* **91**:734-740.
14. Vasan, R.S., Larson, M.G., Benjamin, E.J., and Levy, D. 1995. Echocardiographic reference values for aortic root size: the Framingham Heart Study. *J. Am. Soc. Echocardiogr.* **8**:793-800.
15. Roos, J.E., Willmann, J.K., Weishaupt, D., Lachat, M., Marincek, B., and Hilfiker, P.R. 2002. Thoracic aorta: motion artifact reduction with retrospective and prospective electrocardiography-assisted multi-detector row CT. *Radiology* **222**:271-277.
16. Feuchtner, G.M., Muller, S., Grander, W., Alber, H.F., Bartel, T., Friedrich, G.J., Reinthaler, M., Pachinger, O., zur Nedden, D., and Dichtl, W. 2006. Aortic valve calcification as quantified with multislice computed tomography predicts short-term clinical outcome in patients with asymptomatic aortic stenosis. *J. Heart Valve Dis.* **15**:494-498.
17. Myerson, S.G. 2009. Valvular and hemodynamic assessment with CMR. *Heart Fail Clin.* **5**:389-400; vi-vii.
18. Frank, L., Dillman, J.R., Parish, V., Mueller, G.C., Kazerooni, E.A., Bell, A., and Attili, A.K. 2010. Cardiovascular MR imaging of conotruncal anomalies. *Radiographics* **30**:1069-1094.
19. Burman, E.D., Keegan, J., and Kilner, P.J. 2008. Aortic root measurement by cardiovascular magnetic resonance: specification of planes and lines of measurement and corresponding normal values. *Circ Cardiovasc Imaging.* **1**:104-113; Epub 2008 Jul 30.
20. Lu, T.L., Huber, C.H., Rizzo, E., Dehmeshki, J., von Segesser, L.K., and Qanadli, S.D. 2009. Ascending aorta measurements as assessed by ECG-gated multi-detector

computed tomography: a pilot study to establish normative values for transcatheter therapies. *Eur. Radiol.* **19**:664-669; Epub 2008 Sep 23.

21. Halpern, E.J., Mallya, R., Sewell, M., Shulman, M., and Zwas, D.R. 2009. Differences in aortic valve area measured with CT planimetry and echocardiography (continuity equation) are related to divergent estimates of left ventricular outflow tract area. *AJR Am. J. Roentgenol.* **192**:1668-1673.
22. Ropers, D., Ropers, U., Marwan, M., Schepis, T., Pflederer, T., Wechsel, M., Klinghammer, L., Flachskampf, F.A., Daniel, W.G., and Achenbach, S. 2009. Comparison of dual-source computed tomography for the quantification of the aortic valve area in patients with aortic stenosis versus transthoracic echocardiography and invasive hemodynamic assessment. *Am. J. Cardiol.* **104**:1561-1567.
23. Jeon, M.H., Choe, Y.H., Cho, S.J., Park, S.W., Park, P.W., and Oh, J.K. 2010. Planimetric measurement of the regurgitant orifice area using multidetector CT for aortic regurgitation: a comparison with the use of echocardiography. *Korean J Radiol.* **11**:169-177; Epub 2010 Feb 22.
24. Tsai, I.C., Lin, Y.K., Chang, Y., Fu, Y.C., Wang, C.C., Hsieh, S.R., Wei, H.J., Tsai, H.W., Jan, S.L., Wang, K.Y. et al. 2009. Correctness of multi-detector-row computed tomography for diagnosing mechanical prosthetic heart valve disorders using operative findings as a gold standard. *Eur. Radiol.* **19**:857-867; Epub 2008 Nov 27.