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64-MULTIDETECTOR COMPUTED TOMOGRAPHIC ANGIOGRAPHY OF THE CANINE CORONARY ARTERIES

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Abstract

Canine coronary artery angiography (CTA) was performed in four anesthetized healthy dogs using 64-multi-detector computed tomography. Esmolol, a β -1 adrenergic receptor antagonist, and sodium nitroprusside, an arteriolar and venous dilator, were administered to enhance visualization of the coronary arteries by reducing heart rate and creating vasodilation. The left main coronary artery with its three main branches and the right coronary artery were visualized and subdivided in 13 segments for evaluation. Optimal reconstruction interval, expressed as percentage of the R-to-R interval, was determined at 5% in 2.9%, 35% in 1%, 75% in 21.2%, 85% in 43.3%, and 95% in 31.7% of the segments. Overall image quality was good in 41.3% of the segments and excellent in 14.4%. There was blur in 98.1%, motion in 17.3%, and stair step in 6.7% of the evaluated segments, but these artifacts did not interfere with anatomic depiction of the arteries. Cross-sectional anatomy of the coronary arteries as evaluated from the coronary CTA agreed well with gross anatomic evaluation and published information. The use of esmolol did not lead to the target heart rate of 60–65 beats/min. Nitroprusside had no significant effect on visualized length or diameter of the coronary artery branches. Coronary CTA is useful for the anatomic depiction of coronary artery branches in the dog.

Keywords

dog; heart; MDCT

Introduction

Multidetector computed tomography (MDCT) coronary artery angiography (coronary CTA) has been endorsed for noninvasive evaluation of the coronary arteries in symptomatic human patients.¹ Coronary CTA has been largely facilitated by the introduction of EKG-gated MDCT² and enables visualization of the entire coronary artery tree.^{3,4} The use of 64-MDCT has improved image quality and visibility of small coronary artery branches compared with 16-MDCT.⁵ Also, coronary CTA has been used for the identification and

characterization of anomalous coronary arteries which, in humans, may exhibit malignant variants potentially prone to limited exercise capability and/or sudden death.⁶

Although obstructive coronary artery disease as seen in human patients is not observed commonly in dogs, variations in individual anatomy, such as anomalous coronary arteries in Bulldogs, are important.^{7–9} Such variants must be identified before pulmonic valve balloon dilation as diminished coronary blood flow or avulsion of the coronary artery can result in death.¹⁰

Currently, selective catheter angiography is the gold standard for canine coronary angiography. This is invasive and has the potential of unwanted side effects. It remains used in settings where knowledge of the course of the vessels is vital.¹⁰

Although there are data on canine coronary CTA in basic translational research,¹¹ there is paucity on the anatomic description, diagnostic performance and quality standards, as well as the influence of vasodilating drugs in canine coronary CTA. Therefore, our aim was to test the feasibility of 64-MDCT for visualization of canine coronary arteries. To account for the limited evidence that visualization of the coronary arteries is enhanced in human patients that are pretreated with nitroglycerin derivatives for vasodilation,¹² an anesthetic protocol without and with injectable sodium nitroprusside, a coronary and pulmonary vasodilator, was compared for this purpose.

Material and Methods

General anesthesia was induced in four 1-year-old Beagle dogs (mean body weight = 11 ± 0.5 kg) with propofol* and maintained with isoflurane in 100% oxygen administered via orotracheal tube. End-tidal carbon dioxide levels were kept between 35 and 45 mmHg using a mechanical ventilator.† For individual scans apnea was induced by hyperventilation immediately before the scan. Intravenous crystalloid solution‡ was administered through a 22 G catheter in the left cephalic vein at 10 ml/kg/h with fluid boluses of 5 ml/kg as necessary to maintain blood pressure. Esmolol§ was also administered through this catheter in an attempt to reduce heart rate through β -1 adrenergic receptor antagonism. In each dog, a 100 μ g/kg bolus was given followed by an infusion of 50 μ g/kg/min. However, because heart rate did not decrease, the infusion was increased every 5 min to a maximum of 300 μ g/kg/min.

Scans were started within 15 min following the onset of esmolol infusion. Short (10–15 min) infusions of sodium nitroprusside¶ were also administered through this catheter to provide further arteriolar and venous dilation, although no target blood pressure was set. The second study bolus was performed within 10–15 min of initiating nitroprusside.

Mean blood pressure and heart rate measurements of the examinations without and with nitroprusside were compared using two-tailed paired Student's *t*-test using commercially available software.¶ Significance level was set at $P = 0.05$.

For image acquisition the dogs were placed in dorsal recumbency in a V-trough on a clinical 64-MDCT scanner.** A 20 G catheter was placed in the right cephalic vein for injection of

*Propofol™, Abbott Laboratories, North Chicago, IL.

†SAV 2500, Smiths Medical, Waukesha, WI.

‡Plasma-lyte A, Baxter Healthcare Corporation, Deerfield, IL.

§Bedford Laboratories, Bedford, OH.

¶Hospira Inc., Lake Forrest, IL.

¶Sigma Stat® 3.5, SPSS, Chicago, IL.

**VCT, GE Healthcare, Waukesha, WI.

contrast medium to avoid streak artifacts arising from dense undiluted contrast medium in the cranial vena cava.^{13–15} A test bolus, also called timing bolus, of 5 ml iodinated contrast medium^{††} followed by 20 ml physiologic saline chaser, was injected at 2 ml/s at maximum pressure limits of 300 lb/in.² with a dual barrel power injector.^{‡‡} To monitor contrast medium arrival and to determine time to peak of contrast enhancement repetitive transverse scans were acquired in 1 s time intervals (bolus track setting: 120 kV, 40 mA, axial scanning mode, 5 mm slice thickness) at the level of the heart including the aortic root. Time-to-peak opacification in the ascending aorta was recorded.

The study contrast medium bolus was designed to maximize coronary artery opacification throughout the scan. The contrast medium bolus volume was adjusted to the requirement to cover the entire scan length with sufficient arterial opacification. Therefore, the duration of the planned scan, as a function of scan length divided by pitch, was multiplied by the injection speed to provide the bolus volume. A 30 ml physiologic saline chaser was used to advance the contrast medium through the system while washing contrast medium out of the CrVC and right ventricle to avoid streak artifacts.¹³ This resulted in a total of 1.5–2.6 ml/kg contrast medium per dog. Following the individualized delay to peak enhancement calculated from the test bolus series, the scan of the heart was initiated using helical scan mode at 120 kV, EKG modulated mA (200–750 mA), 350 ms gantry rotation time (average temporal resolution 175 ms using SnapShot Segment feature, proprietary)^{**} 40 mm detector collimation (0.625 mm × 64 detectors), heart-rate adapted variable pitch. Images were reconstructed to 0.625 mm isotropic resolution using a soft tissue reconstruction kernel. The duration of the complete procedure including patient setup, test bolus and coronary scan was approximately 10–15 min per dog; the scan time for coronary angiography itself was dependent on the cranial to caudal FOV, but was approximately 10 s.

After a short break allowing for washout of the contrast medium from the first study bolus, nitroprusside was injected and the study bolus and scan protocol was repeated for each dog. Following the successful termination of the experiment, all dogs underwent euthanasia and necropsy examination.

As part of the postprocessing of data, multiple data sets with the temporal reconstruction window increasing in 10% increments within the cardiac cycle were reconstructed, centered over the 5–95% interval (Fig. 1).

Image evaluation was randomized and performed as a consensus review by one board-certified veterinary radiologist and one board-certified physician radiologist who were unaware of acquisition parameters at the time of evaluation. Window width and level were adjusted individually. Multiplanar and curved reconstructions were applied as needed to optimize visualization of the coronary arteries. Images were reviewed on a dedicated viewing station using specialized software.^{§§} First, injection and vital parameters were assessed. Time-to-contrast medium arrival (time-to-peak enhancement) of the test bolus in the ascending aorta and intensity of enhancement in the ascending aorta resulting from the two study boluses was measured. Heart rate and blood pressure at all three injection times was recorded for each dog. Secondly, evaluation of diagnostic quality of the individual scans was performed by assessment of the left and right coronary arteries and their respective branches. For this, the coronary artery branches were subdivided in segments analogous to branching in people.¹⁴ Then, the reconstruction interval allowing for optimal visualization of each segment was determined. Using the optimal R-to-R reconstruction interval for each

^{††}ISOVUE 370, Bracco Diagnostics Inc., Princeton, NJ.

^{‡‡}Stellant, MedRad, Indianola, PA.

^{§§}VITREA[®]2 Version 4.0, Vital Images, Minnetonka, MN.

segment the overall diagnostic quality of the study was evaluated for visualization of each individual segment (0 = poor, 1 = moderate, 2 = good, 3 = excellent) and presence of artifacts: stair-step, motion or blur (yes/no). Third, the maximal visualized length of the main right and left coronary artery (LCA) branches was measured using a semiautomated vessel track function, and the diameter of those vessels was measured 2 mm distal to their origin. A paired Student's *t*-test was used to determine the effect of nitroprusside on length and diameter. Significance level was set at $P = 0.05$. Lastly, the relation of the visualized coronary arteries and their branches to other cardiac structures was described. The results were compared with the necropsy findings and available references.^{16–18}

Results

64-MDCT coronary CTA was performed successfully in all dogs. Detailed results for vital and injection parameters, measurement of time-to-contrast medium arrival from the test bolus, and intensity of enhancement from the two study bolus in the ascending aorta are given in Table 1. Heart rate, recorded at the time of the scan, was not significantly different between the scans and averaged 111 (range 98–126) beats/min (bpm). No arrhythmias or rapid changes in heart rate were noted at any time. Similarly, the combination of inhalant anesthesia, esmolol, and nitroprusside produced hypotension in all dogs, and mean blood pressure recorded at scan time was not significantly different between scans, averaging 42.7 ± 7.4 mmHg (all $P > 0.05$). Mean time-to-peak enhancement in the ascending aorta from test bolus injection was 6.7 s (range 4–9 s). Adjusting for this interindividual temporal variability from the test bolus arrival, the study bolus produced good enhancement of > 300 Hounsfield units in the ascending aorta in all dogs.

All eight scans were of diagnostic quality. Thirteen coronary artery segments were identified (LCA, LVP 1–3, LS 1–2, LCX 1–4, RCA 1–3, see anatomic definition below). A total of 104 coronary artery segments were evaluated in all eight studies. The optimal reconstruction interval for the individual segments, given as the percentage of the R-to-R interval, was determined at 35% in 1%, 5% in 2.9%, 75% in 21.2%, 95% in 31.7% and 85% in 43.3% of the segments (Table 2). Overall diagnostic quality was rated on a per segment basis, as poor in 8/104 (7.7%), moderate in 38/104 (36.5%), good in 43/104 (41.3%), and excellent in 15/104 (14.4%). Out of the segments rated as poor, 1/8 was the second most proximal segment, all others were third most proximal or further distal segments; for the segments rated with image quality as moderate, 10/38 were the second most proximal segment, all others were third most proximal or further distal segments. Out of the segments rated with overall diagnostic image quality good, 30/43 were within the segment 0–2. For the rating excellent, 13/15 were within segment 0–1 and two were the second most proximal segment.

No artifacts were seen in the main LCA segment in two scans (2/104, 1.9%). Out of the three evaluated artifacts (stair-step, motion, blur) one was observed in 79/104 (76%), two were observed in 21/104 (20.2%), and three artifacts were observed in 2/104 (1.9%) of the coronary artery segments; in summary one or more artifacts were seen in 98.1% of the segments. Blur was the most common artifact and was present in 102/104 (98.1%) of the evaluated segments; motion was present in 18/104 (17.3%), and stair-step artifact was seen in 7/104 (6.7%) of segments. Motion was most commonly present in segments in perpendicular orientation to the scan plane.

Results for length and diameter of the coronary arteries are given in Table 3. In two dogs the exact length of the LCA segment could not be determined in the study without and with injectable vasodilator as the LVP and LCX branches followed a close parallel path before diverging. In those dogs the diameter of the artery was measured as in all other studies.

No significant impact of nitroprusside on length or diameter was found. Although mean blood pressure was lower in the dogs following nitroprusside administration (46.3 ± 7.5 vs. 39.5 ± 8.7 mmHg) these differences were not statistically significant.

The main LCA arose from the left sinus of the aortic bulb in dorsal-left-lateral orientation, just caudal to the level of the main pulmonary artery and medially to the left auricle (Fig. 1A). The short LCA was seen as a distinct segment in two dogs without and with vasodilator. In two dogs the segment was very short and the two main branches (LVIP and LCX) followed a close parallel path before diverging, arising in the same location directly from the aorta (Fig. 1B). Grossly, a short main LCA was present in all dogs, with a length of 3–5 mm and diameter at the opening of 3–4 mm, as described.^{16–18}

The paraconal interventricular branch of the LCA (LIVP) (Fig. 2) was seen as a separate branch in all studies, in one dog arising directly from the aorta, in the other three dogs as branch of the terminal LCA. In all dogs it ran in left ventrolateral and slight caudal orientation almost parallel to the scan plane just caudal to the main pulmonary artery and ventromedially to the left auricle (LIVP 1), to continue very superficially in the paraconal interventricular groove in caudoventral direction almost perpendicular to the scan plane (LIVP 2), turning slightly more parallel to the scan plane toward the apex of the heart (LIVP 3). On gross examination this branch arose as a direct extension of the terminal LCA, and followed the paraconal interventricular groove as described above, with multiple smaller branches. This is in accordance with published information.^{16–18}

The septal branch was seen in all dogs and ran in obliquely horizontal orientation in the interventricular septum (LS 1) and then turned perpendicular to the scan plane to continue as the descending segment (LS 2). In three of the four dogs it arose from the most proximal paraconal interventricular branch of the LCA in both studies; in one of these dogs a separation into two branches was seen at the midlevel of the interventricular septum in both studies. In one dog, two septal branches arose from the medial aspect of the paraconal interventricular branch, one small branch from the proximal LIVP, and one larger one approximately 1 cm distal to its origin, both traveling ventromedially just caudal to the main pulmonary artery into the interventricular septum (Fig. 3). Grossly, the origin of the septal branch was not dissected. A variable origin of the septal branch is reported: 48% from the paraconal interventricular branch, 27% as terminal branch of the LCA, 19% from the LCA, 5% from the aorta, and 1% from the circumflex branch.^{16–18}

The circumflex branch of the LCA (LCX) was seen as a separate artery in all dogs in both studies (Fig. 4). In all dogs the LCX (LCX1) traveled caudally perpendicular to the scan plane, initially laterodorsally adjacent to the aortic root and ventrally adjacent to the left atrial appendage, then continuing caudally in the coronary groove, slightly dorsolaterally adjacent to the left atrioventricular junction, ventrally to the vena cordis magna (left circumflex vein). It continued caudally around the left atrium to the right side almost perpendicular to the scan plane, where it turned very superficially caudoventrally in the subsinuosal interventricular groove (ramus interventricularis subsinuosus, LCX 2) to continue ventrally along the caudolateral wall of the left ventricle almost parallel to the scan plane (LCX 3) to turn perpendicular to the scan plane toward the apex of the heart (LCX 4). The anatomic location of this left coronary branch corresponded to the description in the literature.^{15–20} On gross examination, the position of LCX1 was confirmed but further branches were not examined.

In each scan the right coronary artery (RCA, Figs. 5 and 6) arose in cranioventral direction on midline from the right sinus at the bulb of the aorta at the level of the main pulmonary artery. In one dog a widening of the most proximal portion of the RCA was seen. Grossly,

an accessory RCA was found and could be followed with a probe for 5 mm. The RCA curved in right ventral orientation along the cranioventral aspect of the right atrium and medially to the right ventricle in the coronary groove, initially almost parallel to the transverse plane (RCA 1), then perpendicular to the scan plane as it approached the right lateral aspect of the heart (RCA 2). It continued as right marginal branch (ramus marginalis dextra, RCA 3) caudoventrally along the lateral wall of the right ventricle toward the apex of the heart. The anatomic location of the RCA was in accordance with the literature.^{16–18}

Discussion

Coronary CTA using 64-MDCT enables excellent depiction of the right and LCA and the three main branches of the LCA in the dog.

Heart rate has a major impact on the diagnostic quality of coronary CTA studies. In human patients the target heart rate is 60–65 bpm and is achieved routinely with the use of β -adrenergic receptor antagonism.¹⁶ In an attempt to maintain a heart rate of 60–65 bpm, esmolol was administered to dogs in our study. Esmolol decreases the heart rate and mean arterial blood pressure and prolongs the PR interval in healthy human subjects,^{21,22} and is a safe drug to control heart rate for 64-MDCT coronary CTA in children.²³ In addition, esmolol has been reported to decrease isovolumetric relaxation and myocardial acceleration during isovolumetric relaxation in healthy dogs.²⁴ However, we were unable to reach the target heart rate with esmolol administration. Heart rate remained above the targeted 60–65 bpm, well within the range for normal heart rates of the dog (70–120 bpm). It is possible that heart rate was maintained in a baroreflexive attempt to maintain blood pressure, although general anesthesia blunts this response to an extent.²⁵ Alternatively, esmolol reduces heart rate by blocking the action of endogenous catecholamines (epinephrine and norepinephrine) at the β -1 adrenergic receptor.^{21,22,25} Because the sympathetic nervous system is significantly attenuated during inhalant anesthesia, activation of adrenergic receptors may have been attenuated, reducing the effects of β -1 adrenergic receptor antagonism by esmolol. Although we did not investigate the lack of bradycardia further, alternative techniques, such as calcium channel blockers, to lower heart rate could be assessed.

Hypotension (mean blood pressure <60 mmHg) was severe. Although many factors contribute to hypotension during general anesthesia, the concurrent use of systemic vasodilators (e.g., isoflurane, nitroprusside) and β -1 adrenergic blockade (e.g., esmolol) most likely all played part in the profound hypotension through a reduction in systemic vascular resistance, cardiac output and/or contractility. Thus, these protocols are not recommended for use in clinical patients. Although nitroprusside increases myocardial blood flow and is a potent, short acting coronary artery vasodilator in humans and dogs, an alternate choice may be the use of nitroglycerin which similarly dilates the coronary vasculature but may be associated with less systemic hypotension.^{26,27}

The bolus design was optimized successfully for visualization of the coronary arteries while avoiding artifacts from right heart or cranial vena cava opacification. Based on previous work an optimum bolus profile for this is best achieved using a saline chaser and this was adapted for our study.^{13,19} Bolus volumes were determined arbitrarily focusing on maximal opacification of the coronary arteries and not on weight adaption. The total bolus volume exceeded the commonly used dose of 2 ml/kg in canine vascular CTA and may therefore have to be adapted for translation to the use in clinical patients.

The anatomic visualization of the coronary arteries using coronary CTA was in good agreement with the gross anatomic observation and anatomy reported in the literature.^{16–18} The ability to visualize the normal canine coronary arteries using coronary CTA can serve as

a baseline for visualizing anatomic variants in future studies and in patients. A standard segmental classification system developed by the American Heart Association for reporting of coronary angiography in 1975 is still in use, although a modified version has been proposed.^{20,28} This system was adapted successfully for the canine coronary artery tree and allowed for reproducible description of the canine coronary artery segments. While coronary CTA allows for noninvasive visualization of the coronary arteries in multiple planes, potential drawbacks such as the exposure to increased doses to radiation may have to be considered.

Spiral/helical CT scanners acquire data continuously over the heart cycle and the EKG can be recorded during the scan. The retrospective reconstruction interval (also called window, expressed as R-to-R interval, Fig. 1) can be placed anywhere in the R-to-R interval and images specific for that phase of the cardiac cycle can be displayed using specialized software. Motion of the coronary arteries is continuous during the cardiac cycle, but modest during the mid- to end-diastolic phase just before atrial contraction and at the end of ventricular contraction in human subjects, allowing for motion-poor reconstruction. The optimal visualization has been determined using 4-MDCT for the left anterior descending artery at 60–70%, for the left circumflex artery at 50%, and the RCA at 40% of the R-to-R interval in people indicating the need for separate reconstructions for each coronary artery.²⁹ Using 64-MDCT in people the best image quality was found at 60% and 65% of the R-to-R interval with heart rates < and 65 bpm.^{30,31} In our study the majority of the segments were best displayed at 75–95% of the R-to-R interval. This indicates that there may be a slightly different motion and rotation pattern in the canine heart compared with the human heart. Also, this interval corresponds to diastolic phase of the cardiac cycle, in which coronary blood flow is maximal.

Despite the small size of the canine coronary arteries, and low impact of bradycardic medication in this study, good to excellent overall image quality was achieved in greater than half of the evaluated segments, particularly the proximal to midsegments, allowing for accurate anatomic depiction. Whether canine coronary artery CTA using 64-MDCT is sufficient to detect possible occlusive disease canine patients remains to be determined.

Blur was the most commonly observed artifact, indicating slightly blurred vessel margin depiction. Partial volume effect and motion are the two major underlying reasons for blur. Two strategies to overcome this degradation would be to use a smaller reconstruction interval and reducing motion by improving bradycardic heart rate control or using technology allowing for faster image acquisition. Motion artifact as evaluated in this study occurs due to the motion of arterial vessels that are perpendicular to the scan plane. It is not to be confused with blooming artifact described in human patients from high density calcium deposition in coronary plaques that can have a similar appearance, causing apparent enlargement of the plaque due to partial volume averaging effects.³² It was found, as expected, in segments that are perpendicular to the scanning plane. It is likely to interfere with luminal measurements but did not affect anatomic localization of the segments. Occurrence of stair-step artifact relates to speed of image acquisition and heart rate.³³ Despite the relatively poor efficacy of the bradycardic medication used in this study, stair-step artifact was observed only in 6.7% of the segments. It was, however, present more commonly in the specific image plane but did not affect the coronary artery segment visualization in these instances.

Canine coronary artery length has been reported to be 0.5 cm for the left main coronary artery, 8 cm for the left circumflex branch, 7 cm for the left paraconal interventricular branch, 5 cm for the RCA, with no length being reported for the left septal branch.^{16–18} Length measurements achieved using 64-MDCT coronary CTA were comparable but

slightly shorter, indicating that visualization of the most distal portion of the coronary arteries may have been insufficient. Alternatively differences in breed, body weight or age of the dogs as well as a different definition for the end of the arteries between anatomic specimens and coronary CTA samples may be considered for this discrepancy. The diameter of coronary arteries has been reported as 5 mm for the left main coronary artery, 1.5 mm for the left circumflex and paraconal interventricular branch, and 1.5 mm for the RCA. No measurement was given for the left septal branch.^{16–18} Using coronary CTA the semiautomated measurement of the diameter of all previously described segments was slightly larger, ranging from 2.1 to 3.2 mm; the left septal branch was the smallest measuring 1.8 mm.

Nitroglycerin results in a 20% increase in coronary artery diameter in human subjects and is of critical importance for assessment of the distal coronary artery.²⁶ Due to the relatively smaller size of the coronary arteries in dogs compared with humans the effect of nitroglycerin would be desirable in canine patients undergoing coronary CTA. However, no significant effect on maximally visualized length and maximal diameter was observed using nitroprusside. This may relate to small sample size.

In summary, canine coronary CTA using 64-MDCT was performed successfully and the description can serve as a cross-sectional anatomic reference. Esmolol did not have the desired bradycardic effect and nitroprusside did not enhance visualization of coronary artery branches. Optimal anesthetic protocol and bolus volume need to be determined.

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REFERENCES

1. Budoff MJ, Achenbach S, Blumenthal RS, et al. Assessment of coronary artery disease by cardiac computed tomography: a scientific statement from the American Heart Association Committee on Cardiovascular Imaging and Intervention, Council on Cardiovascular Radiology and Intervention, and Committee on Cardiac Imaging, Council on Clinical Cardiology. *Circulation*. 2006; 114:1761–1791. [PubMed: 17015792]
2. Kalender WA, Seissler W, Klotz E, Vock P. Spiral volumetric CT with single-breath-hold technique, continuous transport, and continuous scanner rotation. *Radiology*. 1990; 176:181–183. [PubMed: 2353088]
3. Hacıoglu Y, Gupta M, Budoff MJ. Noninvasive anatomical coronary artery imaging versus myocardial perfusion imaging: which confers superior diagnostic and prognostic information? *J Comput Assist Tomogr*. 2010; 34:637–644. [PubMed: 20861763]
4. de Graaf FR, Schuijf JD, Delgado V, et al. Clinical application of CT coronary angiography: state of the art. *Heart Lung Circ*. 2010; 19:107–116. [PubMed: 20138806]
5. Wang YN, Jin ZY, Kong LY, et al. Comparison of coronary angiography between 64-slice and 16-slice spiral CT. *Zhongguo Yi Xue Ke Xue Yuan Xue Bao*. 2006; 28:26–31. [PubMed: 16548183]
6. Datta J, White CS, Gilkeson RC, et al. Anomalous coronary arteries in adults: depiction at multi-detector row CT angiography. *Radiology*. 2005; 235:812–818. [PubMed: 15833984]
7. Liu SKTL, Tappe JP, Fox PR. Clinical and pathologic findings in dogs with atherosclerosis: 21 cases (1970–1983). *J Am Vet Med Assoc*. 1986; 189:227–232. [PubMed: 3744984]
8. Buchanan JW. Pulmonic stenosis caused by single coronary artery in dogs: four cases (1965–1984). *J Am Vet Med Assoc*. 1990; 196:115–120. [PubMed: 2295544]
9. Buchanan JW. Pathogenesis of single right coronary artery and pulmonic stenosis in English Bulldogs. *J Vet Intern Med*. 2001; 15:101–104. [PubMed: 11300591]

10. Fonfara S, Martinez Pereira Y, Swift S, et al. Balloon valvuloplasty for treatment of pulmonic stenosis in English Bulldogs with an aberrant coronary artery. *J Vet Intern Med.* 2010; 24:354–359. [PubMed: 20102492]
11. George RT, Ichihara T, Lima JA, Lardo AC. A method for reconstructing the arterial input function during helical CT: implications for myocardial perfusion distribution imaging. *Radiology.* 2010; 255:396–404. [PubMed: 20332374]
12. Chun EJ, Lee W, Choi YH, et al. Effects of nitroglycerin on the diagnostic accuracy of electrocardiogram-gated coronary computed tomography angiography. *J Comput Assist Tomogr.* 2008; 32:86–92. [PubMed: 18303294]
13. Utsunomiya D, Awai K, Sakamoto T, et al. Cardiac 16-MDCT for anatomic and functional analysis: assessment of a biphasic contrast injection protocol. *AJR Am J Roentgenol.* 2006; 187:638–644. [PubMed: 16928924]
14. Kerl JM, Ravenel JG, Nguyen SA, et al. Right heart: split-bolus injection of diluted contrast medium for visualization at coronary CT angiography. *Radiology.* 2008; 247:356–364. [PubMed: 18372454]
15. Cao L, Du X, Li P, Liu Y, Li K. Multiphase contrast-saline mixture injection with dual-flow in 64-row MDCT coronary CTA. *Eur J Radiol.* 2009; 69:496–499. [PubMed: 18313876]
16. Evans, HE. The heart and the arteries. In: Evans, HE., editor. *Miller's anatomy of the dog.* Philadelphia: Saunders; 1993. p. 598-601.
17. Koch, T.; Berg, R. Blutgefäß- und Lymphsystem, Angiologia. In: Koch, T.; Berg, R., editors. *Lehrbuch der Veterinär-Anatomie: Die grossen Versorgungs- und Steuerungssysteme.* Stuttgart: Gustav Fischer Verlag Jena; 1993. p. 45-62.
18. König, H.; Liebich, HG. Organe des Herz-Kreislauf-systems. In: Koenig, HE.; Liebich, HG., editors. *Anatomie der Haussäugetiere.* Stuttgart: Schattauer GmbH; 2005. p. 445-448.
19. Bae KT. Intravenous contrast medium administration and scan timing at CT: considerations and approaches. *Radiology.* 2010; 256:32–61. [PubMed: 20574084]
20. Austen WG, Edwards JE, Frye RL, et al. A reporting system on patients evaluated for coronary artery disease. Report of the Ad Hoc Committee for Grading of Coronary Artery Disease, Council on Cardiovascular Surgery, American Heart Association. *Circulation.* 1975; 51:5–40. [PubMed: 1116248]
21. Alexander R, Binns J, Hetreed M. A controlled trial of the effects of esmolol on cardiac function. *Br J Anaesth.* 1994; 72:594–595. [PubMed: 7911029]
22. Ellenbogen KA, McCarthy EA, Pritchett EL. Effects of bolus injection of esmolol in healthy, exercising subjects. *Clin Pharmacol Ther.* 1987; 41:455–459. [PubMed: 3829581]
23. Rigsby CK, Defreitas RA, Nicholas AC, et al. Safety and efficacy of a drug regimen to control heart rate during 64-slice ECG-gated coronary CTA in children. *Pediatr Radiol.* 2010; 40:1880–1889. [PubMed: 20499055]
24. Hori Y, Kunihiro S, Kanai K, Hoshi F, Itoh N, Higuchi S. The relationship between invasive hemodynamic measurements and tissue-doppler-derived myocardial velocity and acceleration during isovolumic relaxation in healthy dogs. *J Vet Med Sci.* 2009; 71:1419–1425. [PubMed: 19959890]
25. Stoelting, RK.; Hillier, SC. Pharmacology & physiology in anesthetic practice. In: Stoelting, RK.; Hillier, SC., editors. *Anesthetics in pharmacology & physiology in anesthetic practice.* Philadelphia: Lippincott Williams & Wilkins; 2006. p. 42-86.
26. Capurro NL, Kent KM, Epstein SE. Comparison of nitroglycerin-, nitroprusside-, and phentolamine-induced changes in coronary collateral function in dogs. *J Clin Invest.* 1977; 60:295–301. [PubMed: 406277]
27. Pagani M, Vatner SF, Braunwald E. Hemodynamic effects of intravenous sodium nitroprusside in the conscious dog. *Circulation.* 1978; 57:144–151. [PubMed: 618382]
28. Konuralp C, Idiz M, Ates M. A novel reporting approach to coronary angiography: “segmental coding system.”. *Int J Cardiol.* 2005; 98:113–121. [PubMed: 15676175]
29. Kopp AF, Schroeder S, Kuettner A, et al. Coronary arteries: retrospectively ECG-gated multi-detector row CT angiography with selective optimization of the image reconstruction window. *Radiology.* 2001; 221:683–688. [PubMed: 11719663]

30. Leschka S, Husmann L, Desbiolles LM, et al. Optimal image reconstruction intervals for non-invasive coronary angiography with 64-slice CT. *Eur Radiol.* 2006; 16:1964–1972. [PubMed: 16699752]
31. Rahmani N, Jeudy J, White CS. Triple rule-out and dedicated coronary artery CTA: comparison of coronary artery image quality. *Acad Radiol.* 2009; 16:604–609. [PubMed: 19282205]
32. Zhang S, Levin DC, Halpern EJ, Fischman D, Savage M, Walinsky P. Accuracy of MDCT in assessing the degree of stenosis caused by calcified coronary artery plaques. *AJR Am J Roentgenol.* 2008; 191:1676–1683. [PubMed: 19020235]
33. Kimura F, Umezawa T, Asano T, et al. Coronary computed tomography angiography using prospective electrocardiography-gated axial scans with 64-detector computed tomography: evaluation of stair-step artifacts and padding time. *Jpn J Radiol.* 2010; 28:437–445. [PubMed: 20661694]

Fig. 1. For retrospective EKG gating the reconstruction interval, also called reconstruction window, is expressed as the percentage of the R-to-R interval.

Fig. 2.

Transverse images of the paraconal interventricular branch of the left coronary artery (LPIV), reconstructed at 95% (A) and 5% (B) of the R-to-R interval. At 5% reconstruction interval, motion artifact causes the false display of two vessels and blur, whereas only mild blur is evident using the 95% reconstruction interval.

Fig. 3. Variation of the branching pattern of the left coronary artery in three dogs displayed as thick-slice reconstruction (6.48 mm): The left circumflex (LCX), left interventricular paraconalis (LIVP) and left septal (LS) branch arise from the short coronary artery as separate branches (A), but when the main left coronary artery is very short, this may appear as direct branching off the LCX and LIVP off the aorta (B). Variation of the branching pattern with two separate branches of the LS was seen in one dog (C).

Fig. 4. Circumflex branch of the left coronary artery (LCX): Curved multiplanar reconstruction (A, B) and transverse images (C, D) reconstructed at 85% (A, C) and 65% (B, D) of the R-to-R interval. Reconstruction at the suboptimal reconstruction interval leads to stair-step artifact in the plane of the artery (B) and motion (D). Mild blur is evident even at optimal reconstruction interval due to limits in resolution, but this does not impact the anatomic localization of the coronary artery branch.

Fig. 5. Curved multiplanar reconstruction at the level of the right coronary artery (RCA) reconstructed at 75% (A) and 25% (B) of the R-to-R interval. Reconstruction at the suboptimal interval at 25% causes increased blur and introduces stair-step artifact. Stair-step artifact, however, is not in the image plane of the right coronary artery and does not interfere with anatomic depiction of this vessel.

Fig. 6. Motion artifact in the right coronary artery on transverse plane reconstruction is increased from 75% (A) to 95% (B) reconstruction interval of the R-to-R interval. Motion artifact can be observed when the vessel runs perpendicular to the imaging plane.

Table 1

Results for Injection and Vital Parameters: Heart Rate, Blood Pressure, Time of Test Bolus Arrival in the Ascending Aorta, Study Bolus Design and Intensity of Enhancement in the Ascending Aorta from the Two Study Bolus for the Four Dogs

	Test Bolus				Study Bolus 1				Study Bolus 2			
	HR (bpm)	mBP (mmHG)	TTP aAO (s)	HR (bpm)	mBP (mmHG)	Bolus (ml 100% Iodinated Contrast Medium/ml Saline)	Enhancement aAO (HU (SD))	HR (bpm)	mBP (mmHG)	Bolus (ml 100% Iodinated Contrast Medium/ml Saline)	Enhancement aAO (HU (SD))	HR (bpm)
Dog 1	105	40	6	112	49	18/30	407 (17)	117	29	18/30	301 (18)	117
Dog 2	122	50	6	126	50	20/30	347 (19)	124	50	20/30	347 (19)	124
Dog 3	100	44	4	98	51	18/30	523 (18)	108	38	18/30	396 (21)	108
Dog 4	105	35	9	113	35	30/30	597 (21)	110	41	30/30	431 (19)	110

Before injection of study bolus 2 a vasodilator was injected intravenously. HR, heart rate; TTP, time-to-peak enhancement in ascending aorta after test bolus injection; aAO, ascending aorta; mBP, mean blood pressure; HU, Hounsfield units; bpm, beats/min.

Table 2

Optimal Reconstruction Interval Displayed as Percentage of the R-to-R Interval for the Individual Coronary Artery Segments Observed on Exams Without and With Injection of Vasodilator in the Total of 104 Segments Evaluated

	% Reconstruction Interval (Number of Segments)				
	5%	35%	75%	85%	95%
LCA 0			2	3	3
LIVP 1			1	6	1
LIVP 2			2	5	1
LIVP 3			1	4	3
LS 1			2	3	3
LS 2			2	3	3
LCX 1			1	1	6
LCX 2			1	5	2
LCX 3	1		2	3	2
LCX 4		1	1	4	2
RCA 1			2	3	3
RCA 2	1		2	3	2
RCA 3	1		3	2	2
Overall	3	1	22	45	33

LCA, left main coronary artery; LIVP, interventricular paraaonalis branch of left coronary artery; LS, septal branch of left coronary artery; LCX, circumflex branch of left coronary artery; RCA, right coronary artery.

Averages of Maximally Visualized Length of the Main Coronary Artery Branches using Semi-Automated Vessel Track Function and Maximal Diameter Measured 2 mm Distal to Origin of the Individual Segment Observed Without and With Injection of Vasodilator

Table 3

	Length (mm)		Diameter (mm)	
	w/o Nitro	w Nitro	w/o Nitro	w Nitro
LCA	4.8 *	4.3 *	2.9	3.2
LIVP	68.6	62.5	3.1	2.9
LS	34.1	33.0	1.8	1.8
LCX	73.2	71.3	3.2	3.1
RCA	41.2	37.5	2.1	2.3

* n = 2.

RCA, right coronary artery; LCA, main left coronary artery; LIVP, interventricular paraconalis branch of left coronary artery; LS, septal branch of left coronary artery; LCX, circumflex branch of left coronary artery; w/o nitro, without injection of vasodilator nitroprusside; w nitro, with injection of vasodilator nitroprusside.