THE UNIVERSITY of EDINBURGH

Edinburgh Research Explorer

Vascular conspicuity differs among injection protocols and scanner types for canine multiphasic abdominal computed tomographic angiography

OPEN ACCESS

ORIGINAL INVESTIGATION

WILEY

Vascular conspicuity differs among injection protocols and scanner types for canine multiphasic abdominal computed tomographic angiography

Florence Thierry[1] (iD) | Jennifer Chau[2] | Mariano Makara[2] | Swan Specchi[3] (iD) | Edoardo Auriemma[3] | Maurizio Longo[1] (iD) | Ian Handel[1] (iD) | Tobias Schwarz[1] (iD)

[1]The Royal (Dick) School of Veterinary Studies and Roslin Institute, The University of Edinburgh, Roslin, EH25 9RG, UK

[2]Faculty of Veterinary Science, University of Sydney, New South Wales, 2006, Australia

[3]Istituto Veterinario di Novara, Granozzo con Monticello, Novara, Italy

Correspondence
Dr. Tobias Schwarz, The Royal (Dick) School of Veterinary Studies and Roslin Institute, The University of Edinburgh, Roslin, EH25 9RG, UK.
Email: tobias.schwarz@ed.ac.uk

Abstract

Multiphasic multidetector computed tomographic angiography is a standard diagnostic test for canine abdominal vascular disorders. Three imaging protocols have been previously described. The test-bolus protocol allows precise timing but can be time consuming to perform. Bolus-tracking software is fast and easy to use but can be problematic for exact timing of vascular phases. A recently described fixed-injection-duration protocol is not influenced by body weight and provides a wider temporal window for arterial acquisitions. Objectives of this retrospective and prospective, multicentric, method comparison study were to determine which of the three multidetector computed tomographic angiography protocols allows best vascular conspicuity of the canine abdomen and to assess the influence of different multidetector computed tomography (CT) scanners on study quality. Triple-phase multidetector computed tomographic angiography canine abdominal studies from 30 dogs were retrospectively retrieved from three different institutions. Each institution performed one of the three computed tomographic angiography protocols (4-row and 16-row multidetector CT). Prospectively, the three protocols were also acquired with similar conditions on a 64-row MDCT in 21 dogs. Main abdominal vessels were scored by blinded readers for each phase. The fixed-injection-duration protocol had the best combined arterial and portal vascular conspicuity on scanners of limited speed, while the test-bolus protocol provided the best overall vascular conspicuity on 64-row multidetector CT scanner. The quality of arterial studies performed on 64-row MDCT scanner was improved compared to the ones performed on four- to 16-row multidetector CT scanners. Findings supported the fixed-injection-duration protocol as the best compromise between an ideal portal vascular enhancement and an easily reproducible protocol on scanners with low and high number of detector rows.

KEYWORDS
angiographic, arterial, dog, multidetector CT, portal

1 | INTRODUCTION

Multiphasic multidetector computed tomographic angiography is currently a standard diagnostic test for canine vascular disorders such as portosystemic shunts, arteriovenous fistulae, or vascular tumor invasion.[1–3] This method is also commonly used for characterizing parenchymal disease such as pancreatic insulinoma and may help characterizing benign and malignant lesions.[4–8] A major advantage of multiphasic multidetector computed tomographic angiography is the ability to separate the arterial from the portal and systemic venous phases in order to reach an optimal visualization of each vascular bed and to identify hypervascular or hypovascular parenchymal lesions.[9]

The test-bolus multidetector computed tomographic angiography protocol has been used for more than a decade in veterinary

patients.[2,10,11] This protocol is based on the initial injection of a low dose of contrast medium, i.e., test bolus, to determine the peak of aortic and portal enhancement using time attenuations curves followed by a dynamic angiography with a full dose of contrast agent. This technique has the advantage of being specifically adapted to the patient, which is valuable in animals with impaired cardiovascular function. The bolus-tracking multidetector computed tomographic angiography protocol uses software tools to monitor the arrival of contrast medium into a vessel and triggers an automatic or manual start of the acquisition once the preset density threshold has been reached. This type of protocol provides an individualized timing of the arterial phase.[8,12,13] The fixed-injection-duration multidetector computed tomographic angiography protocol is another technique that has been recently described in cats and dogs using a fixed injection duration of 20 s and adjusted injection rate.[14–16] This new method triggers a later and lower peak of aortic enhancement with good separation between the arterial and portal phases. An advantage of this new technique is a more homogeneous pattern of vascular enhancement regardless of the body weight. Another advantage is a wider temporal window for acquiring the arterial phase.

A previous study compared bolus-tracking and test-bolus techniques for thoracic computed tomographic angiography in healthy beagles and did not identify differences in image quality, consistent with previously published data in human medicine.[17,18] An increasing number of publications have described multiphasic multidetector computed tomographic angiography protocols for investigations of parenchymal disorders.[5–7] However, the choice of a particular abdominal multidetector computed tomographic angiography protocol may possibly influence the parenchymal enhancement and have an impact on subsequent results. New multidetector computed tomography (CT) scanners have been recently introduced that have a higher number of detector rows and can therefore offer shorter acquisition times.[19] A detailed comparison of different multidetector computed tomographic angiography protocols was not found in the veterinary literature.

The aim of this study was to compare the conspicuity of vessels in the cranial abdomen using three different protocols of triple-phase multidetector computed tomographic angiography (test-bolus, bolus-tracking, and fixed-injection-duration protocols). We also aimed to determine which protocol allows the best vascular visualization and to assess the influence of the canine weight and different multidetector CT scanners on the quality of the studies. We hypothesized that there is a difference in vascular conspicuity between the three multidetector computed tomographic angiography protocols and that the quality of these studies depends on the number of detector rows used and body weight.

2 | MATERIALS AND METHODS

2.1 | Sample population

This retrospective and prospective, multicentric, method comparison study gathered triple-phase abdominal multidetector computed tomographic angiography studies performed on dogs under general anes-

thesia presented for clinical reasons unrelated to the abdominal vasculature. Decisions for study inclusion and exclusion were made by a final year small animal imaging resident (F.T.). Studies were included if the injection of contrast medium was performed via a cephalic vein and if the arterial, portal and late venous phases included the abdomen from the diaphragm to the caudalmost kidney margin. Dogs were excluded if any vascular impairment or malformation was present in the abdomen. Images were acquired in ventral recumbency under general anesthesia during apnea following hyperventilation in order to avoid motion artifacts. A precontrast study of the abdomen was acquired in all dogs. All contrast medium injections were performed with a power injector without the use of saline chaser. All late venous phases were performed within 5 min after contrast medium injection.

2.2 | Retrospective computed tomographic data

Canine abdominal multidetector computed tomographic angiography studies were retrospectively retrieved from three different institutions. The sample size for each institution group was matched and based on the maximal number of studies available at the University of Edinburgh that fitted the inclusion criteria. Each institution performed one of the three multidetector computed tomographic angiography protocols. As part of the inclusion criteria, the same test-bolus protocol was performed at the Royal (Dick) School of Veterinary Studies of the University of Edinburgh with the following protocol. First, a 0.5 mL/kg bolus of contrast medium (185 mg Iodine/kg) was injected. A dynamic acquisition in a single location at the porta hepatis was performed at the start of the contrast medium injection every 2 s during 40 s. Regions of interest were placed in the aorta and portal vein by an imaging resident or a board-certified veterinary radiologist. Time attenuation curves were used to establish optimal timings for the arterial and portal acquisitions. The arterial acquisition delay was set at the peak of aortic contrast enhancement. The minimum interscan delay was 4 s. The portal delay was initiated shortly before peak portal enhancement or following the minimum reset time between two phases. The full bolus of contrast medium (700–740 mg I/kg) was injected at 3 mL/s in dogs weighing less than 10 kg and at 5 mL/s if over 10 kg as per previous publication.[10] The arterial phase was performed in a caudo-cranial direction, the portal and late venous phase were scanned in a cranio-caudal direction.

The bolus-tracking protocol was performed at the Istituto Veterinario di Novara. As part of the inclusion criteria, the following protocol was used. A premonitoring transverse scan was set at the cranial aspect of the diaphragm, and designated as the start location of the arterial acquisition. A region of interest was placed in the aorta by an imaging resident, and the automated bolus-tracking set at 100 Hounsfield units (HU) with a cycle time of 3 s. The bolus of contrast medium (700 mg I/kg) was performed in all dogs at 3 mL/s. The arterial phase was run in a cranio-caudal direction, the portal phase scanned immediately after the minimum reset time in a caudo-cranial direction and the late venous phase in a cranio-caudal direction. The minimum interscan delay was 2 s.

The fixed-injection-duration protocol was performed at the University of Sydney. As part of the inclusion criteria, the following protocol

was followed. Bolus-tracking software and fixed delay times after contrast arrival were used for the arterial and portal scans. Contrast medium was injected over 20 s for all dogs and the injection rate was adjusted accordingly. A pre-monitoring transverse scan was set at the cranial aspect of the diaphragm. A region of interest was placed in the aorta by an imaging resident and the automated bolus-tracking set at 100 HU with a cycle time of 2 s. The time-to-aortic-arrival was defined as the time elapse from the beginning of the contrast medium injection to the time when the aortic attenuation reached 100 HU. The delay for arterial acquisition was similar for all dogs and equal to 10 s after time-to-aortic-arrival in order to scan during the arterial peak or immediately after. The minimum interscan delay was 2 s. The portal acquisition was automatically triggered 35 s after time-to-aortic-arrival. The arterial phase was run in a cranio-caudal direction, the portal phase scanned in a caudo-cranial direction, and the late venous phase in a cranio-caudal direction.

2.3 | Prospective computed tomographic data

Twenty-one canine abdominal computed tomographic angiography studies were prospectively acquired at the Royal (Dick) School of Veterinary Studies of the University of Edinburgh. The sample size was chosen based on a consensus opinion of the authors, one of whom was a statistician. The Veterinary Ethics and Welfare Committee of the Royal (Dick) School of Veterinary Studies of the University of Edinburgh granted approval for the prospective study prior to publication (Veterinary Ethics and Welfare Committee reference 106.17). The test-bolus, bolus-tracking, and fixed-injection-duration protocols were identical to the retrospective part of the study but performed on a 64-row multidetector CT scanner (Somatom® Definition AS Siemens, Erlangen, Germany). Injections of 700 mg I/kg of Iopamidol (Niopam 350®, Bracco UK Ltd) were performed with Empower CTA®+ Injector System (Bracco® injeneering S.A., Milan, Italy) set with a maximum pressure of 325 psi. Dogs were randomly allocated to a protocol according to their weight in order to achieve similar body weight distribution in each group of seven dogs. All acquisitions were performed by the same operator (F.T.). Scan settings included a collimator pitch of 1.4, tube potential of 100–120 kVp, reference tube current of 250–320 mA, slice thickness of 2 mm, matrix 512×512, and reconstruction with low frequency algorithms. Scan tube current was modulated by an automatic exposure control system (Care Dose 4D, Siemens Medical Solutions, International). The minimum interscan delay was 2 s.

2.4 | Computed tomographic data recorded

All retrospective multidetector computed tomographic angiography studies were randomized, reviewed by a board-certified veterinary radiologist (T.S.) and an imaging resident (F.T.), and scored by consensus. All studies were anonymized and reviewers were blinded to the angiographic protocol used. All assessments and measurements were performed using dedicated DICOM viewer software (OsiriX v5.8.5 64-bit, Geneva, Switzerland). A window width of 350 HU and a window level of 100 HU were used in order to allow optimal visualization of vascular streaming artifacts. The abdomen was divided into three

regions of different vascular beds. During the arterial phase, each main abdominal vessel was subjectively scored using a binary grading system (+1 or –1). The same process was repeated for the portal phase. The most cranial abdominal region was established from the cranial aspect of the liver to the first hepatic vein ramification allowing scoring of the aorta and caudal vena cava. The mid-abdominal region extended from the first hepatic vein ramification to the gastroduodenal vein entrance into the portal vein, allowing scoring of the aorta, hepatic arteries, caudal vena cava, hepatic veins, intrahepatic portal branches, and extrahepatic portal vein. The caudal abdominal region included the portion of the abdomen between the gastroduodenal vein entrance into the portal vein and the jejunal veins, allowing scoring of the aorta, celiac and cranial mesenteric arteries, caudal vena cava, extrahepatic portal vein, gastroduodenal vein, and splenic vein. For example, to achieve a satisfactory score of +1 in the aorta during the arterial phase, the aorta had to present with a homogeneous strong vascular enhancement and absence of contrast streaming artifact. An ideal arterial phase of a computed tomographic angiography was defined as having strong contrast enhancement in the aorta, hepatic arteries, and celiac arteries but none in the systemic venous and portal vasculature (Figure 1). The portal phase was considered optimal if the entire portal vasculature, splenic vein included, presented strong contrast enhancement compared to the caudal vena cava and hepatic veins (Figure 2). During the arterial phase, the arterial index was equal to the summation of all vascular scores given for the three abdominal regions. The maximal arterial index was 15 and minimal arterial index –15. Similarly, the portal index resulted from the sum of all scores given for the abdominal vessels during the portal phase. The maximal portal index was 10 and minimal portal index –10. We summed both arterial and portal indices to create a combined vascular index. The same subjective scoring process was repeated for the prospective multidetector computed tomographic angiography studies.

A small animal imaging resident (F.T.) performed a quantitative scoring by placing a 10 mm^2 region of interest in the main abdominal vessels during the arterial and portal phases. A region of interest was placed as appropriate in the aorta, caudal vena cava, and portal vein in the three abdominal regions. The attenuation values were then averaged per dog and per phase for each vessel. Any vascular or extra-vascular artifact was recorded. The same quantitative scoring process was repeated for the prospective multidetector computed tomographic angiography studies.

2.5 | Data analyses

Statistical analysis was performed by a statistician (I.H.) using a free software (R Core Team 2017, R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria). We investigated the relationship between weight, scan duration, scanner type, and protocol on index for the two phases separately and in combination using a linear regression model with index as the dependent variable. Although index is derived from ordinal scores the overall index was treated as a numerical variable. Models were assessed by inspection of histograms of their residuals. Summary estimates of the relationship between protocol and index
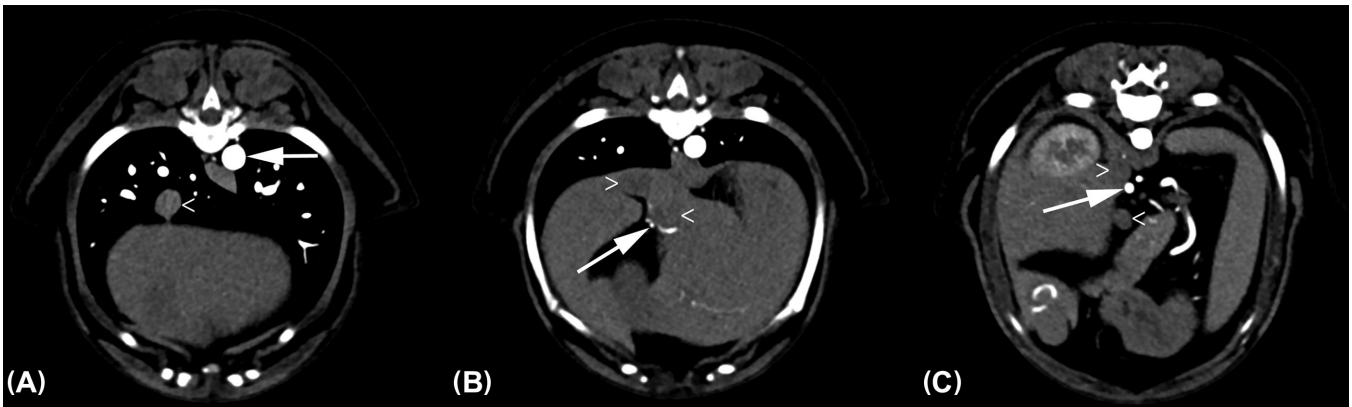
FIGURE 1 Optimal arterial phase illustrated by a transverse plane for each abdominal region (A–C) in a dog using the bolus-tracking protocol on 64-row multidetector computed tomography unit. Note the strong contrast enhancement in the aorta, celiac and hepatic arteries (arrows) but none in the portal and venous vasculature (arrowheads)

were estimated using the Least-Squares means (Lsmeans) R-package and reported as estimate and 95% confidence interval. In order to investigate any difference of scan duration between four- and 16-slice CT units, a Kruskal–Wallis test was performed. The significance level for statistical tests was set at 0.05.

3 | RESULTS

3.1 | Retrospective computed tomographic data

A total of 30 dogs were included in the sample (10 dogs from each institution). At the Royal (Dick) School of Veterinary Studies of the University of Edinburgh, computed tomographic images were acquired using the test-bolus protocol with a four-row multidetector CT unit (Somatom® Volume Zoom, Siemens, Germany) over a 6-year period. Scan settings included slice thickness 3 mm, pitch between 1 and 1.5, tube potential 120 kVp, tube current 120–150 mA, matrix 512×512. Injections of 350–370 mg I/mL Iopamidol (Niopam®, Bracco UK Ltd)

were performed with Mark V power injector (Medrad®, PA, USA) set at 300 psi injection pressure.

At the Istituto Veterinario di Novara, computed tomographic images were acquired using the bolus-tracking protocol with a 16-row MDCT unit (Light Speed, GE Medical Systems, Milan, Italy) over a 8-month period. Scan settings included slice thickness between 1.25 and 2.5 mm, pitch 0.938, tube potential 100–120 kVp, tube current 180–200 mA, matrix 512×512. Injections of 350 mg I/mL of iohexol (Omnipaque®, GE Healthcare, Princeton, NJ) were performed with Medrad® envision CT injector (Medrad Italia, Cava Manara, Italy) set at 300 psi injection pressure.

At the University of Sydney, computed tomographic images were acquired using the fixed-injection-duration protocol with a 16-row MDCT unit (Phillips 16 Slice, Brilliance® CT V2.3, Phillips Medical Systems Netherlands, the Netherlands) over a 6-month period. Scan settings included slice thickness between 1 and 2 mm, pitch between 0.813 and 0.938, tube potential 120 kVp, tube current 100–250 mA, matrix 512×512. Injections of 350 mg I/mL of iohexol (Omnipaque®, GE Healthcare, Princeton, NJ) were performed with Empower CTA®
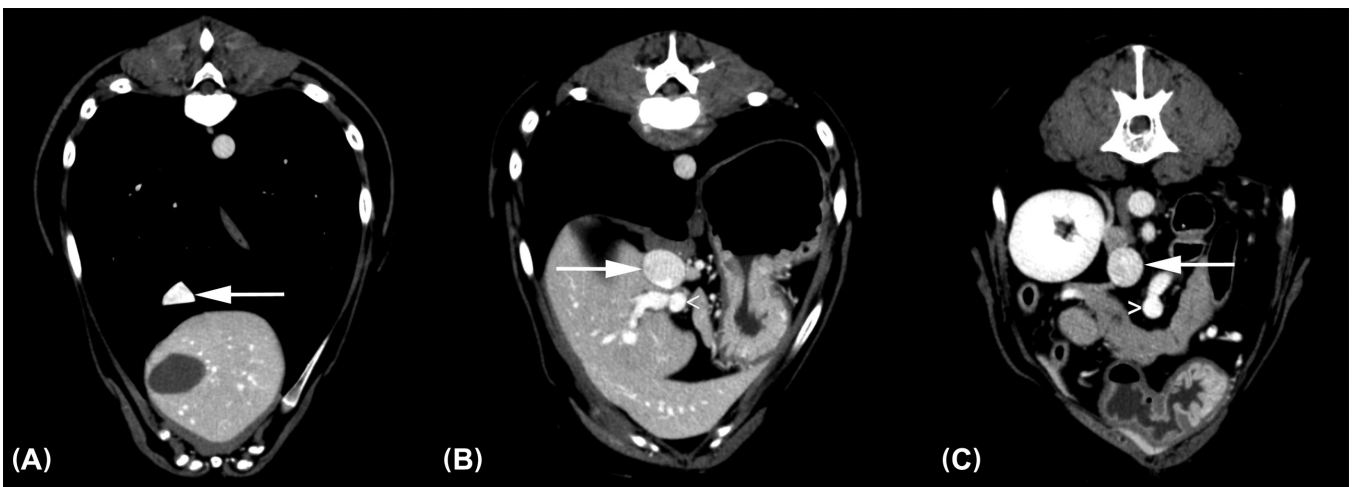

FIGURE 2 Optimal portal phase illustrated by a transverse plane for each abdominal region (A–C) in a dog using the fixed-injection-duration protocol on 16-row multidetector computed tomography unit. Note the strong contrast-enhancement in the portal vein (arrowhead) in comparison to the caudal vena cava (arrow)
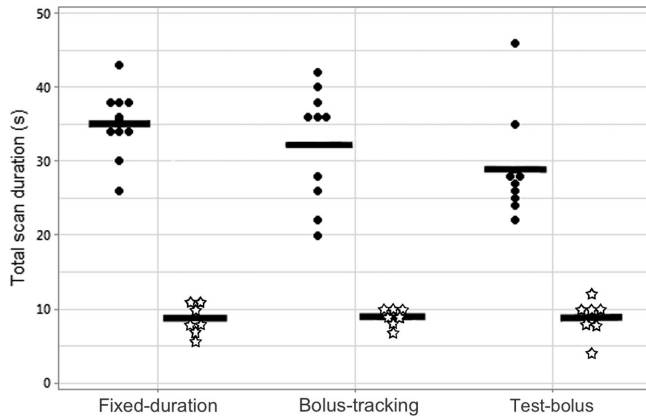
FIGURE 3 Dotplot representing the total scan duration (sum of arterial scan and portal scan duration in seconds) for each protocol and multidetector computed tomography scanner (●, four- and 16-row multidetector computed tomography scanners; ✳, 64-row multidetector computed tomography scanner; —, mean)

power injector (E-Z-EM Inc., Westbury, New York) set at 300 psi injection pressure.

Various breeds were represented. The median weight of dogs was 12 kg ($n = 10$, range: 7–38 kg) in the test-bolus group, 26 kg ($n = 10$, range: 7–47 kg) in the bolus-tracking group, and 24 kg ($n = 10$, range: 7–43 kg) in the fixed-injection-duration group. The test-bolus group gathered seven female and three male dogs, the bolus-tracking group, five females and five males, and the fixed-injection-duration group, four female and six male dogs. The median age of dogs was 5 years ($n = 10$, range: 0.3–12 years) in the test-bolus group, 9 years ($n = 10$, range: 2–14 years) in the bolus-tracking group, and 5 years ($n = 10$, range: 2–11 years) in the fixed-injection-duration group. Among all groups, nine of 30 dogs had no significant abnormality and nine of 30 dogs had a final diagnosis of neoplasia. Other disorders included hepatopathy (3/30), thoracic or subcutaneous abscesses (2/30), nephropathy (2/30), lymphadenomegaly (2/30), ureteral ectopia (1/30), gastric foreign body (1/30), and pelvic fracture (1/30). In the test-bolus group, the portal acquisition was initiated following the minimum reset time between two phases in seven dogs. These seven dogs were small breed dogs weighing up to 15 kg. The median injection rate for the fixed-injection-duration protocol was 2.3 mL/s ($n = 10$, range: 0.7–4.3 mL/s). The median time-to-aortic-arrival of the contrast medium bolus was 9 s ($n = 10$, range: 2–14 s) for the test-bolus protocol, 15 s ($n = 10$, range: 4–19 s) for the bolus-tracking protocol, and 15 s ($n = 10$, range: 8–22 s) for the fixed-injection-duration protocol. The median time for initiation of the portal acquisition scan was 15 s after time-to-aortic-arrival ($n = 10$, range: 10–17 s) for the test-bolus protocol, 28 s after time-to-aortic-arrival ($n = 10$, range: 21–32 s) for the bolus-tracking technique, and 35 s after time-to-aortic-arrival ($n = 10$, range: 35–35 s) for the fixed-injection-duration protocol. Duration of the arterial and portal scans is summarized in Figure 3. The total scan duration was not significantly different between the four-slice CT scanner and both 16-slice CT units ($n = 30$, $df = 2$, $\chi^2 = 4.43$, $P = 0.109$). These scanners were therefore grouped together in the following linear regression models.

The mean indices are summarized in Table 1. During the arterial phase, the fixed-injection-duration protocol had the narrowest disper-

sion of data. Quantitatively, the arterial phase of the test-bolus protocol had the highest mean arterial index compared to the other two protocols, while the portal phase of the fixed-injection-duration protocol offered the highest mean portal index. Overall, the fixed-injection-duration protocol has the highest mean combined vascular index and narrowest dispersion of data.

On the arterial phase of the fixed-injection-duration protocol, contrast enhancement was visible in the portal vein at the porta hepatis in nine of 10 dogs consistent with a late arterial acquisition. In the test-bolus group during the portal phase, contrast streaming artifact was reported in the portal vein in four dogs and in the caudal vena cava in six dogs. This artifact was less commonly noted in the bolus-tracking group (2/10 dogs) and the fixed-injection-duration group (4/10 dogs) during the portal phase.

During the arterial phase, the mean aortic attenuation was quantitatively higher for the test-bolus protocol compared to the bolus-tracking and fixed-injection-duration protocols (Table 2). These two last protocols nevertheless achieved acceptable aortic enhancement. During the portal phase, the mean aortic attenuation was lower for the fixed-injection-duration protocol compared to the test-bolus and bolus-tracking protocols.

3.2 | Prospective computed tomographic data

Various breeds were represented among which Retrievers (7/21) and collie (3/21) breeds were common. The median weight of dogs was 25 kg ($n = 7$, range: 5–37 kg) in the test-bolus group, 25 kg (N = 7, range: 6.5-36 kg) in the bolus-tracking group and 19 kg (N = 7, range: 9-36 kg) in the fixed-injection-duration group. Each group gathered 3 female and 4 male dogs. The median age of dogs was 8 years (N = 7, range: 2-10 years) in the test-bolus group, 11 years (N = 7, range: 6-16 years) in the bolus-tracking group and 10 years (N = 7, range: 0.6–11 years) in the fixed-injection-duration group.

Among all groups, 15/21 dogs had a final diagnosis of neoplasia while one of 21 dogs had no significant abnormality. Other disorders included pulmonary disease (2/21), sialadenitis (1/21), brachycephalic obstructive airway syndrome (1/21), and retrobulbar abscess (1/21). The median injection rate for the fixed-injection-duration protocol was 2.0 mL/s ($n = 7$, range: 0.9–3.6 mL/s). The median time-to-aortic-arrival of the contrast medium bolus was 10 s ($n = 7$, range: 9–14 s) for the test-bolus protocol, 11 s ($n = 7$ range: 5–15 s) for the bolus-tracking protocol and 10 s ($n = 7$, range: 7–12 s) for the fixed-injection-duration protocol. The median time for initiation of the portal acquisition scan was 11 s after time-to-aortic-arrival ($n = 7$, range: 7–18 s) for the test-bolus protocol, 8 s after time-to-aortic-arrival ($n = 7$, range: 7–14 s) for the bolus-tracking technique and 35 s after time-to-aortic-arrival ($n = 7$, range: 35–35 s) for the fixed-injection-duration protocol. Duration of the arterial and portal scans is summarized in Figure 3.

The mean indices are summarized in Table 1. The arterial phase of the bolus-tracking protocol had the highest mean arterial index and narrowest dispersion of data compared to the other two protocols. The portal phase of the fixed-injection-duration protocol offered the highest mean portal index and narrowest dispersion of data. The

TABLE 1 Arterial, portal, and combined indices for each protocol and multidetector computed tomography scanner

		Test-bolus protocol	Bolus-tracking protocol	Fixed-injection-duration protocol
4 and 16 MDCT (*n* = 3)	Mean arterial index	7.9 (SD 7.1)	2.4 (SD 6.2)	3.1 (SD 3.4)
	Mean portal index	1 (SD 5.3)	6.2 (SD 3.6)	7.2 (SD 3.9)
	Mean combined arterial and portal index	8.9 (SD 10.4)	8.6 (SD 8.2)	10.3 (SD 6.1)
64-row MDCT (*n* = 2)	Mean arterial index	11.3 (SD 4.4)	15 (SD 0)	4 (SD 2.8)
	Mean portal index	2.9 (SD 5.0)	−1.1 (SD 3.2)	8 (SD 2)
	Mean combined arterial and portal index	14.1 (SD 4.7)	13.9 (SD 3.2)	12 (SD 4.5)

Abbreviation: MDCT, multiphasic multidetector computed tomography; SD, standard deviation.

mean bolus-tracking portal index, on the other hand, was lower than the two other protocols due to a very premature acquisition. Overall, the test-bolus protocol had the highest mean combined vascular index.

On the arterial phase of the fixed-injection-duration protocol, contrast enhancement was visible in the portal vein at the porta hepatis in five of dogs consistent with a late arterial acquisition. In the bolus-tracking group during the portal phase, contrast streaming artifact was present in the portal vein in all seven dogs and in the caudal vena cava in five dogs (Figure 4). This artifact remained common in the test-bolus group (4/7 dogs) but was never present in the studies of the fixed-injection-duration group during the portal phase.

During the arterial phase, the mean attenuation in the portal vein and caudal vena cava was quantitatively higher for the fixed-injection-duration protocol compared to the other two protocols, consistent with a late arterial acquisition (Table 2). During the portal phase, the mean aortic attenuation was quantitatively lower for the fixed-injection-duration protocol compared to the test-bolus and bolus-tracking protocols.

3.3 | Linear regression model for combined vascular index

The factor scan duration was found to be non-significant and strongly correlated to the scanner type ($\rho = 0.836$). This factor was dropped from initial model, which was then re-estimated.

The variable weight (estimate ± standard error = −0.043 ± 0.043, $t = 0.991$, $P = 0.324$) and scanner type (estimate ± standard error = −2.130 ± 1.195, $t = −1.783$, $P = 0.078$) had no significant effect on the combined index. This combined index for the fixed-injection-duration protocol was not significantly different from the test-bolus (estimate ± standard error = 0.073 ± 1.436, $t = 0.051$, $P = 0.959$) or from the bolus-tracking protocol (estimate ± standard error = −0.380 ± 1.460, $t = −0.260$, $P = 0.795$) (Figure 5).

3.4 | Separated linear regression models for arterial and portal phases

Similarly, the factor scan duration was found to be non-significant and strongly correlated to the scanner type ($\rho = 0.815$ for the arterial phase

TABLE 2 Vascular contrast attenuation in Hounsfield units during the arterial and portal phase for each protocol and multidetector computed tomography scanner

			Test-bolus protocol	Bolus-tracking protocol	Fixed-injection-duration protocol
4- and 16-row MDCT (*n* = 30)	Arterial phase	Mean aortic attenuation	760 (SD 438)	433 (SD 132)	556 (SD 159)
		Mean portal attenuation	86 (SD 62)	114 (SD 42)	123 (SD 60)
		Mean caudal vena cava attenuation	119 (SD 81)	158 (SD 43)	179 (SD 72)
	Portal phase	Mean aortic attenuation	314 (SD 93)	250 (SD 49)	207 (SD 69)
		Mean portal attenuation	268 (SD 79)	249 (SD 59)	236 (SD 66)
		Mean caudal vena cava attenuation	240 (SD 77)	218 (SD 48)	205 (SD 56)
64-row MDCT (*n* = 21)	Arterial phase	Mean aortic attenuation	713 (SD 132)	757 (SD 351)	604 (SD 104)
		Mean portal attenuation	99 (SD 46)	52 (SD 29)	145 (SD 71)
		Mean caudal vena cava attenuation	120 (SD 55)	49 (SD 16)	168 (SD 55)
	Portal phase	Mean aortic attenuation	370 (SD 101)	363 (SD 227)	244 (SD 36)
		Mean portal attenuation	246 (SD 47)	226 (SD 100)	263 (SD 45)
		Mean caudal vena cava attenuation	262 (SD 91)	216 (SD 86)	228 (SD 41)

Abbreviation: MDCT; multiphasic multidetector computed tomography, SD; standard deviation.
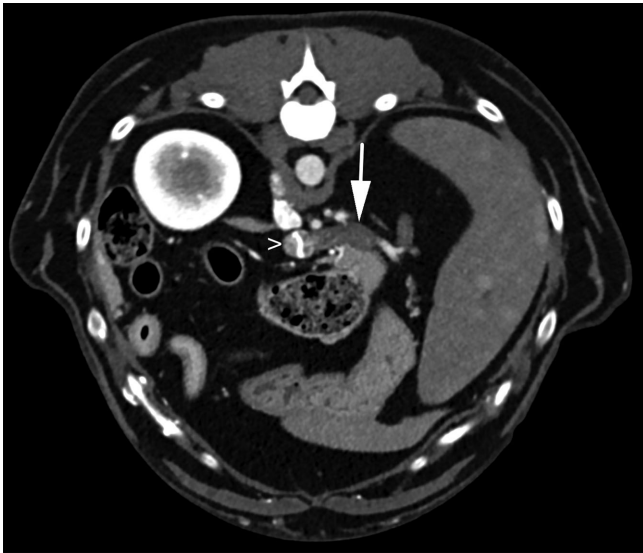
FIGURE 4 Portal phase in a dog using the bolus-tracking protocol on a 64-row multidetector computed tomography unit. Note the contrast streaming artifact in the portal vein (arrowhead) due to arrival of unenhanced blood from the splenic vein (arrow)

and $\rho = 0.857$ for the portal phase). This factor was dropped from initial models, which were then re-estimated.

The variable weight had no significant effect on the arterial index (estimate ± standard error = 0.105 ± 0.054, $t = 1.930$, $P = 0.060$). The scanner type (four- to 16-row unit vs. 64-row unit) had a significant effect on the arterial index (estimate ± standard error = −5.866 ± 1.502, $t = -3.905$, $P = 0.0003$). Indeed the arterial studies performed on the 64-row scanner had significantly higher arterial indices. The arterial index of the fixed-injection-duration was significantly lower and different from the test-bolus protocol (estimate ± standard error = 5.931 ± 1.805, $t = 3.285$, $P = 0.002$) but not different from the bolus-tracking protocol (estimate ± SE = 3.474 ± 1.835, $t = 1.893$, $P = 0.065$) (Figure 6A).

For the portal phase, the variable weight (estimate ± standard error = −0.019 ± 0.047, $t = -0.411$, $P = 0.683$) and scanner type (esti-
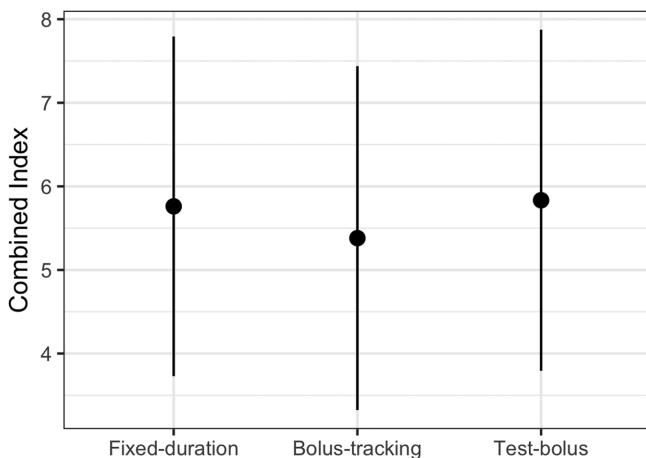

FIGURE 5 Dotplot representing the corrected mean (lsmean) combined index with 95% confidence intervals for each protocol on all four-, 16-, and 64-row multidetector computed tomography scanners
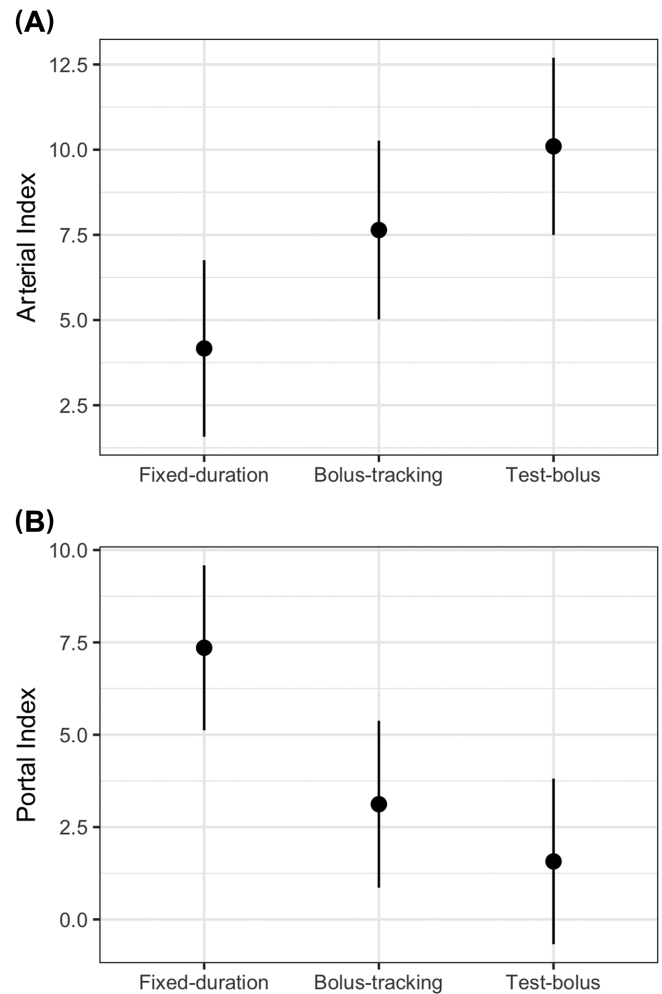

FIGURE 6 Dotplot representing the corrected mean (lsmean) arterial index (A) and portal index (B) with 95% confidence intervals for each protocol on all four-, 16-, and 64-row multidetector computed tomography scanners

mate ± standard error = 1.605 ± 1.295, $t = 1.240$, $P = 0.221$) had no significant effect on the portal index. The portal index of the fixed-injection-duration was significantly higher and different from the test-bolus protocol (estimate ± standard error = −5.784 ± 1.556, $t = -3.717$, $P = 0.0005$) and from the bolus-tracking protocol (estimate ± standard error = −4.235 ± 1.582, $t = -2.677$, $P = 0.010$) (Figure 6B).

4 | DISCUSSION

Findings from this study support our primary hypothesis in that there was a difference of vascular conspicuity between protocols during the arterial and portal phase in the separated linear regression model. The quality of arterial studies performed on the 64-row multidetector CT scanner was improved compared to the ones performed on four- to 16-row multidetector CT scanners. This effect was not demonstrated during the portal phase. Contrary to our last hypothesis, body weight had no effect on image quality.

The lack of difference in overall vascular conspicuity between the different protocols in the combined linear regression model does not

fully reflect the more detailed results for each vascular phase. In fact, the test-bolus and bolus-tracking protocols provided arterial studies of better quality than the fixed-injection-duration protocol while it was the contrary during the portal phase, and these effects cancelled each other out. In order to interpret the specificity of each protocol during each phase, we chose to focus the rest of our discussion based on the separated linear regression model.

The choice of protocol had an effect on the quality of studies. The test-bolus protocol offered the best arterial conspicuity on a four-row multidetector CT scanner, while the bolus-tracking protocol exceeded this quality on a 64-row multidetector CT scanner. This finding highlights that an automated scan trigger associated with a fast scanning time produces the best arterial result. Indeed, the use of bolus-tracking software also allows individual variations such as cardiac output and triggers the acquisition sooner if the bolus of contrast medium has an early arrival. The fixed-injection-duration protocol offered the best portal vascular conspicuity of multidetector computed tomographic angiography studies performed on slow and fast multidetector CT units. This result confirms that a slow and fixed injection duration yields homogeneous and strong portal enhancement due to its wide bolus geometry.

On 64-row multidetector CT unit, the fixed-injection-duration protocol scoring results suffered because the arterial phase was often scanned too late. To optimize the arterial phase of the fixed-injection-duration protocol, we have since the cessation of the study shortened the arterial scan delay after time-to-aortic-arrival from 10 s to 7 s with good empirical results. This avoids streaming artifacts in veins, which can be confused with arterial flow. By using a shorter arterial delay on a 64-row multidetector CT unit, the overall arterial conspicuity is expected to reach similar excellent quality as the bolus-tracking protocol on such a fast scanner.

Our hypothesis that image quality depends on the number of detector rows of a CT scanner was confirmed for the arterial phase but not for the portal phase. The arterial phase was of higher quality on a 64-row MDCT scanner. Indeed, a low number of detector rows represents a limitation to the scanner speed. By increasing detector row numbers in multidetector CT, scanning time is reduced, and thus, the image quality is more homogeneous for each vascular phase.[19] On fast CT units, bolus-tracking software is optimal to trigger an arterial phase of excellent quality as shown in this study. In practice, on MDCT scanners with a low number of detector rows, the portal phase of the bolus-tracking protocol can be run immediately after the arterial phase and result in a study of acceptable quality. Unfortunately, if the exact same protocol is run on a fast multidetector CT unit, like in the prospective part of this study, it will trigger a very premature portal phase. The absence of optimal portal timings explains the overall low quality of the portal phase using the bolus-tracking protocol on 64-row multidetector CT scanner. Previous publications have established optimal delays using bolus-tracking technique for the pancreas and liver, although the need for organ-specific delays is not practical for daily use.[8,13] Weight is another variable that has to be taken into account for the bolus-tracking protocol since the time-to-arterial peak is influenced by body weight when the injection rate is fixed.[14] The bolus-tracking protocol needs to be adapted for fast multidetector CT scanners with a high number of detector rows by establishing longer delays between the arterial and portal phases.

Depending on the protocol and the multidetector CT scanner used, studies had wide to narrow variation of quality. Overall, the fixed-injection-duration and the bolus-tracking protocol presented the narrowest data dispersion for all phases combined. These two protocols are therefore better reproducible compared to the test-bolus technique. This finding may be related to human errors. Indeed, for the test-bolus protocol, the operator has to select the optimal timings on the time-attenuation curves of the test bolus, which is often done by observing a graph, rather than using displayed time figures. The retrospective studies of the test-bolus protocol highlighted an unexpected wide variation of quality. The low number of detector rows and long scan duration are likely responsible for this qualitative variation during the arterial phase. The variation in portal phase imaging is more difficult to explain. The time-attenuation curve of the portal phase is supposed to be the shape of a plateau,[10,11] however, in reality it is often more shaped like a wedge, with a steep rise and slow decline. Operators had no instructions which time point to choose from the portal attenuation curve, which likely introduced variability in vascular conspicuity. If the phase of the test-bolus protocol is, for example, acquired at the beginning of the portal plateau, as performed for some of the data of this study, it will likely result in poorer quality of the portal enhancement with contrast streaming artifact arising from the non-enhanced splenic vein. Establishing the optimal portal timing on time-attenuation curves was considered by the authors as the main source of variability of the portal phase and limitation to the test-bolus protocol. Another possible reason explaining the poor quality of some test-bolus studies is the potential discrepancy between timings established via a small test bolus of contrast medium and the real timings after a full bolus of contrast medium. Indeed, a test bolus has a different volume and dose in relation to body weight compared to the full bolus of contrast medium causing different bolus geometry.[12,17,20] Its optimal arterial and portal timings may not be representative of the optimal delays of a full bolus.

The fixed-injection-duration protocol was designed to suppress the variability of vascular enhancement due to weight and to have a wide temporal window to acquire the arterial phase.[14] A slow injection of contrast medium over 20 s triggers a later and lower aortic peak enhancement due its wider bolus geometry.[14–16,21] On four- and 16-row multidetector CT scanners, the aortic attenuation during the arterial phase was indeed lower compared to the test-bolus protocol but higher than the bolus-tracking protocol. On 64-row multidetector CT scanner, the three protocols had similar aortic attenuation during the arterial phase. The bolus-tracking protocol had nevertheless a wide distribution of data for the aortic attenuation. For a fixed injection rate, the time to arterial peak is influenced by body weight.[14] A short acquisition time thus increases the variability of aortic attenuations between dogs of different body weights. Overall, the choice of protocol for the arterial phase appears to have little impact on the aortic contrast enhancement. During the portal phase, however, the aortic contrast enhancement was lower with the fixed-injection-duration protocol. This is most likely due to a later portal acquisition compared to the other two protocols.

Surprisingly, the scan duration had no effect on vascular conspicuity in this study. It has been suggested that contrast medium injection rate should be increased with fast CT acquisition in order to match the fast scanning duration.[16,19] The disadvantage of decreasing the injection duration is the narrowing of the temporal window for the arterial scan. Given the good quality of the portal phase of the fixed-injection-duration protocol, we therefore recommend to keep a long injection duration of 20 s for this protocol.

Contrast streaming artifact was commonly reported in early-performed portal studies. Non-contrast enhanced blood of the splenic vein mixes with contrast-enhanced blood in the portal vein and causes this artifact when the portal phase is performed too early. In the caudal vena cava, contrast streaming artifact is visible when early renal contrast-enhancing venous flow mixes with non-enhancing caval blood. In the authors' opinion, streaming artifact in the caudal vena cava or portal vein can be considered as a good marker of a premature portal phase. In the test-bolus group, 11/17 studies demonstrated this vascular artifact during the portal phase while it was rarely noted in the fixed-injection-duration group. On a 64-row multidetector CT unit, the portal phases of the bolus-tracking group were all performed too early, which was confirmed by the low portal index and commonly reported contrast streaming artifact.

Due to the multicentric nature of the study, different MDCT scanners have been used by different operators, which may have influenced the quality of the acquisitions. Several anesthetic protocols have been performed, which may have triggered different cardiovascular response and affected the timings of vascular enhancement. Indeed, it has been demonstrated that peak and time to peak of aortic contrast-enhancements increase when the cardiac output is reduced due to an increased circulation time.[20,22] It does however reflect the reality of daily practice. Having larger groups of dogs might have yielded further meaningful statistics. Due to the retrospective nature of part of the study, the median weight of dogs in the test-bolus group was smaller compared to the other groups, which may have affected the vascular conspicuity.

In conclusion, the three multidetector computed tomographic angiography protocols yielded different abdominal vascular conspicuity. The fixed-injection-duration protocol performed by multiple operators had the best vascular conspicuity on scanners of limited speed, while the test-bolus protocol performed by a single operator provided the best vascular conspicuity on fast MDCT scanner. The number of detector rows influenced the quality of the arterial phase due to scanner speed limitation but it did not affect the quality of the portal phase. In the authors' opinion, the main disadvantages of the test-bolus protocol were the increased dose of contrast medium required, and being operator dependent. Authors propose that the fixed-injection-duration protocol offers a good compromise between an ideal vascular enhancement during the portal phase and an easily reproducible protocol on scanners with low and high number of detector rows. For the arterial acquisition of this protocol, we recommend improving it by using a fixed delay of 7 s after time-to-aortic-arrival and keeping the delay of 35 s after time-to-aortic-arrival for the portal acquisition.

LIST OF AUTHOR CONTRIBUTIONS

Category 1

(a) Conception and Design: Thierry F, Chau J, Makara M, Specchi S, Auriemma E, Longo M, Handel I, Schwarz T

(b) Acquisition of Data: Thierry F, Chau J, Makara M, Specchi S, Auriemma E, Longo M, Handel I, Schwarz T

(c) Analysis and Interpretation of Data: Thierry F, Handel I

Category 2

(a) Drafting the Article: Thierry F

(b) Revising Article for Intellectual Content: Thierry F, Chau J, Makara M, Specchi S, Auriemma E, Longo M, Handel I, Schwarz T

Category 3

(a) Final Approval of the Completed Article: Thierry, Chau J, Makara M, Specchi S, Auriemma E, Longo M, Handel I, Schwarz T

ORCID

Florence Thierry iD http://orcid.org/0000-0003-4175-4397
Swan Specchi iD http://orcid.org/0000-0001-6148-4000
Maurizio Longo iD http://orcid.org/0000-0002-6838-8430
Ian Handel iD http://orcid.org/0000-0001-6407-4963
Tobias Schwarz iD http://orcid.org/0000-0001-8412-573X

REFERENCES

1. Zwingenberger AL, Schwarz T, Saunders M. Helical computed tomographic angiography of canine portosystemic shunts. *Vet Radiol Ultrasound*. 2005;1:27–32.

2. Frank P, Mahaffey M, Egger C, Cornell KK. Helical computed tomographic portography in ten normal dogs and ten dogs with a portosystemic shunt. *Vet Radiol Ultrasound*. 2003;4:392–400.

3. Zwingenberger AL, McLear RC, Weisse C. Diagnosis of arterioportal fistulae in four dogs using computed tomographic angiography. *Vet Radiol Ultrasound*. 2005;46:472–477.

4. Caceres AV, Zwingenberger AL, Hardam E, Lucena JM, Schwarz T. Helical computed tomographic angiography of the normal canine pancreas. *Vet Radiol Ultrasound*. 2006;3:270–278.

5. Mai W, Caceres AV. Dual-phase computed tomographic angiography in three dogs with pancreatic insulinoma. *Vet Radiol Ultrasound*. 2008;49:141–148.

6. Kutara K, Seki M, Ishikawa C, Sakai M, Kagawa Y, Lida G, et al. Triple-phase helical computed tomography in dogs with hepatic masses. *Vet Radiol Ultrasound*. 2014;55:7–15.

7. Jones ID, Lamb CR, Drees R, Priestnall SL, Mantis P. Associations between dual-phase computed tomography features and histopathologic diagnoses in 52 dogs with hepatic or splenic masses. *Vet Radiol Ultrasound*. 2016;57:144–153.

8. Choi SY, Lee I, Seo JW, Park HY, Choi HJ, Lee YW. Optimal scan delay depending on contrast material injection duration in abdominal

multi-phase computed tomography of pancreas and liver in normal Beagle dogs. *J Vet Sci*. 2016;17:555–561.

9. Bae KT. Intravenous contrast medium administration and scan timing at CT: Considerations and approaches. *Radiology*. 2010;256:32–61.

10. Zwingenberger AL, Schwarz T. Dual-phase CT angiography of the normal canine portal and hepatic vasculature. *Vet Radiol Ultrasound*. 2004;2:117–124.

11. Winter MD, Kinney LM, Kleine LJ. Three-dimensional helical computed tomographic angiography of the liver in five dogs. *Vet Radiol Ultrasound*. 2005;6:494–499.

12. Mehnert F, Pereira PL, Trübenbach J, Kopp AF, Claussen CD. Biphasic spiral CT of the liver: automatic bolus tracking or time delay? *Eur Radiol*. 2001;11:427–431.

13. Choi S-Y, Choi H-J, Lee K-J, Lee Y-W. Establishment of optimal scan delay for multi-phase computed tomography using bolus-tracking technique in canine pancreas. *J Vet Med Sci*. 2015;77:1049–1054.

14. Makara M, Dennler M, Kühn K, Kalchofner K, Kircher P. Effect of contrast medium injection duration on peak enhancement and time to peak enhancement of canine pulmonary arteries. *Vet Radiol Ultrasound*. 2011;52:605–610.

15. Makara M, Chau J, Hall E, Kloeppel H, Podadera J, Barrs V. Effects of two contrast injection protocols on feline aortic and hepatic enhancement using dynamic computed tomography. *Vet Radiol Ultrasound*. 2015;56:367–373.

16. Chau J, Young AC, Dhand N, Makara MA. Estimation of time to peak contrast enhancement of the aorta and liver for dual-phase computed tomography on the basis of contrast medium arrival time, injection duration, and injection technique in dogs. *Am J Vet Res*. 2016;77: 1093–1100.

17. Cassel N, Carstens A, Becker P. The comparison of bolus tracking and test bolus techniques for computed tomography thoracic angiography in healthy beagles. *JSAVA*. 2013;84:930–939.

18. Kerl JM, Lehnert T, Schell B, Bodelle B, Beeres M, Jacobi V, et al. Intravenous contrast material administration at high-pitch dual-source CT pulmonary angiography: Test bolus versus bolus-tracking technique. *Eur J Radiol*. 2012;81:2887–2891.

19. Hallett RL, Fleischmann D. Tools of the trade for CTA: MDCT scanners and contrast medium injection protocols. *Tech Vasc Interv Radiol*. 2006;9:134–142.

20. Bosch B, Alef M, Ludewig E, Hause A, Oechtering G, Kiefer I. Multiphasic contrast-enhanced CT: correlation of the peak attenuation in the aorta abdominalis and portal vein with easily detectable clinical parameters. *Tierarztl Prax*. 2013;41:23–30.

21. Lee SK, Lee D, Kim D, Cha A, Choi J. Effect of catheter size and injection rate of contrast agent on enhancement and image quality for triple-phase helical computed tomography of the liver in small dogs. *Vet Radiol Ultrasound*. 2017;58:664–670.

22. Bae KT, Heiken JP, Brink JA. Aortic and hepatic contrast medium enhancement at CT. Part II. Effect of reduced cardiac output in a porcine model. *Radiology*. 1998;207:657–662.