Whole-heart 4D flow cardiac magnetic resonance in healthy dogs

N.S. Pfammatter[1], I.U. Campagna[2], M. Baron Toaldo[3], E. Bruellmann[4], H. Richter[1], P.R. Kircher[1], M. Dennler[1]

[1] Clinic of Diagnostic Imaging, [2] Section of Anaesthesiology and [3] Division of Cardiology, Vetsuisse Faculty, University of Zurich, Switzerland, [4] Philips AG, Zurich, Switzerland

Dr. Baron Toaldo's present address is Department of Veterinary Medical Sciences, Alma Mater Studiorum, University of Bologna, Ozzano Emilia, Italy.

Abstract

In cardiac magnetic resonance imaging (CMR), accurate flow measurements rely on perpendicular plane-alignment with flow direction. For 2D phase contrast (PC) cardiac magnetic resonance measurements, planes have to be defined during the examination of the heart, which is time consuming and error-prone. Collection of flow information of the entire volume of the heart by a 4D flow CMR postpones plane alignment to post-processing. Sampling of such a large amount of data requires acceleration of data acquisition with techniques such as SENSitivity Encoding (k-t SENSE) or Broad-use Linear Acquisition Speed-up Technique (k-t BLAST). Objectives of the study were to compare 4D flow CMR, accelerated with two different acceleration methods with the established 2D PC CMR based on assessment of stroke volume at all four cardiac valves. The values of stroke volume acquired with the 4D flow CMR SENSE did not differ significantly when compared to the 2D PC CMR SENSE at the left side of the heart (aortic and mitral valve). Significant differences between the techniques were seen at the pulmonic and tricuspid valves. Acceleration with k-t BLAST revealed significantly lower values of stroke volume at all cardiac valves, except at the mitral valve.

Keywords: cardiac flow quantification, canine, 4D magnetic resonance imaging, k-t SENSE, k-t-BLAST, phase contrast angiography

4D Flussmessungen im Herzen mit kardialer Magnetresonanztomographie bei gesunden Hunden

Bei der Herzuntersuchung mittels Magnetresonanztomographie (CMR) muss die Ebene für akkurate Flussmessungen senkrecht zur Blutflussrichtung definiert werden. Im 2D Phasenkontrast (PC) CMR erfolgt die Wahl der Ebene schon während der Untersuchung, was zeitaufwendig und problemanfällig ist. Mit der Messung aller Blutflussinformationen des gesamten Herzens mittels einer 4D flow CMR, verschiebt sich die Wahl der Ebenen in die Nachbearbeitung. Das Sammeln solch grosser Datenmengen erfordert eine Beschleunigung der Messtechnik wie SENSitivity Encoding (k-t SENSE) oder Broad-use Linear Acquisition Speed-up Technique (k-t BLAST). Das Ziel dieser Studie war, die 4D flow CMR, beschleunigt mit zwei verschiedenen Methoden, mit der etablierten 2D PC CMR anhand der Bestimmung des Schlagvolumens über allen vier Herzklappen zu vergleichen. Die Werte der Schlagvolumenmessung für die linke Seite des Herzens (Aorten- und Mitralklappe), durchgeführt anhand der 4D flow CMR k-t SENSE, waren nicht signifikant verschieden im Vergleich zu den Messungen mittels der 2D PC CMR k-t SENSE. An der Pulmonal- und Trikuspidalklappe zeigten sich jedoch signifikante Unterschiede zwischen diesen beiden Techniken. Die Beschleunigung durch k-t-BLAST ergaben generalisiert tiefere Werte des Schlagvolumens an allen Herzklappen, ausser der Mitralklappe.

Schlüsselwörter: Herzflussmessung, 4D Magnetresonanztomographie, k-t SENSE, k-t BLAST, Phasenkontrastangiographie

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Introduction

Cardiac magnetic resonance imaging (CMR) gains popularity in veterinary diagnostic imaging (Vallee et al., 2004; Gilbert et al., 2010). CMR in animals is used for evaluation of cardiac morphology (Contreras et al., 2008; Baumwart et al., 2009; Drees et al., 2015), cardiac function (Hockings et al., 2003; MacDonald et al., 2005; Baumwart et al., 2009; Kim et al., 2013; Meyer et al., 2013; Sieslack et al., 2013; Sieslack et al., 2014; Drees et al., 2015; Drees et al., 2015) as well as associated diseases of the heart (MacDonald et al., 2006; MacDonald et al., 2006; Mai et al., 2010), the pericardium (Boddy et al., 2011), and the adjacent vasculature (Mai et al., 2010; Lee et al., 2017). Comparison of stroke volume based on a flow-sensitive phase-contrast sequence in different anatomical locations provides important clinical information such as cardiac output, shunt fraction, collateral flow around obstructions and flow differences in the pulmonary arteries (Gatehouse et al., 2005). A recently published study (Dennler et al., 2017) compared different methods of evaluation of stroke volume using a cine gradient echo sequence and a two-dimensional (2D) phase contrast (PC) CMR sequence in healthy dogs. The stroke volume of the left and right ventricle was measured based on morphology and compared with measurements of the stroke volume over all four cardiac valves acquired with a 2D PC CMR. The study showed, that evaluation based on flow quantification was more robust than using morphology to calculate the stroke volume. But flow quantification relies on perpendicular alignment of the region of interest (ROI) with flow direction (Bogaert et al., 2012). Therefore, planes in accurate position have to be defined before acquisition of the sequence, which is time consuming, error-prone and highly operator dependent (Lotz et al., 2002; Sargent et al., 2015; Dennler et al., 2017). To overcome this limitation, collection of cardiac flow information with a three-dimensional time-resolved (4D) flow CMR method including the whole heart allows plane alignment to post-processing (Brix et al., 2009; Attili et al., 2010, Stankovic et al., 2013), which allows reduction of anesthesia time as a single sequence is used to acquire all data from the whole heart and adjacent vasculature. The increasing application of 4D flow CMR in human medicine for intra- and extra-cardiac flow quantification resulted in a universal consensus statement about its use in 2015. (Dyverfeldt et al., 2015).

Sampling such a large amount of data in clinical patients requires acceleration of image acquisition with techniques such as SENSitivity encoding (k-t SENSE) or Broad-use Linear Acquisition Speed-up Technique (k-t BLAST). The acceleration with k-t SENSE works as parallel imaging technique and achieves a shortening in acquisition time by reducing lines in k-space. The signals and sensitivities from a multi-element phase-array surface coil are combined in one image. The individual coil element information is used to unfold the aliasing of the data due to reduction of phase-encoding steps. The acceleration with k-t BLAST represents a different approach to accelerate imaging of dynamic objects. Repetitive imaging of static objects, such as the thoracic wall or the liver, produces redundant data. Focusing on the variable fractions in the image by measuring exclusively alternating data reduces false investment of scan time. The k-t BLAST technique uses two steps for acquisition of high-resolution images without aliasing. A first step generates an under-sampled image that would exhibit multiple fold-over artifacts if reconstructed conventionally. A second step, the training stage acquires an estimate of the novel, moving parts in the image and allows reconstruction of the image without aliasing (Stadlbauer et al., 2009; Attili et al., 2010; Stadlbauer et al., 2010; Carlsson et al., 2011).

Objectives of our study were to compare stroke volume at the aortic (AV), pulmonic (PV), mitral (MV) and tricuspid (TV) valves using whole-heart 4D flow CMR accelerated with k-t SENSE and k-t BLAST with a 2D PC CMR accelerated with k-t SENSE. The hypothesis was that no significant differences occur measuring stroke volume with different methods at all four cardiac valves.

Animals, Material and Methods

Animals

Seven healthy Beagle dogs were included in the study, 2 males and 5 females with a mean age of 3.1 ± 0.2 years and a mean body weight of 13.1 ± 2.8 kg. The dogs were considered healthy based on clinical examination, blood and urine analysis as well as echocardiographic examination by a cardiology resident (MBT). All procedures of the study followed the guidelines established by the Animal Welfare Act of Switzerland and the Cantonal Veterinary Office approved the study design (license number 144/2013).

Anesthesia

Each dog was premedicated with midazolam (Dormicum, Roche Pharma AG; Reinach, Switzerland; 0.1 mg/kg, i.m.) and butorphanol (Morphasol, Dr. E. Graeub AG; Bern, Switzerland; 0.2 mg/kg i.m.) followed by placement of an intravenous catheter. General anesthesia was induced with propofol (Propofol 1%, Fresenius Kabi AG; Oberdorf, Switzerland; 4 to 6 mg/kg i.v.) and after orotracheal intubation maintained with isoflurane (IsoFlo; Abott AG; Altishofen, Switzerland) combined in oxygen and room air (fraction of inspired oxygen (FIO_2) of 0.6-0.7). Simultaneously, the dogs received intravenous crystalloid Lactated Ringer's Solution (Ringer-Lactate, 5ml/kg/h, Fresenius Kabi AG, Oberdorf, Switzerland). The patients obtained positive pressure ventilation (Mallard, Mallard Medical; U.K.) in a volume-controlled mode (10-15 ml/kg) with adaptation of the respiratory rate to achieve an end-tidal carbon dioxide of 40 mmHg (5.3 kPa). The dogs were placed in dorsal recumbency with the head towards the gantry.

Electrocardiography

Cardiac electrical activity was monitored with a wireless vector cardiography unit (VCG) (Philips AG; Zurich, Switzerland) with four MR-safe electrodes (750 Clear Tape Electrodes, KendallTM, Anandic 110 Medical System SA; Feuerthalen, Switzerland) placed at the thoracic wall at the level of the heart. A peripheral pulse (PPU) unit (Philips AG; Zurich, Switzerland) served as monitor of mechanical cardiac performance. Respiration navigation was used in the volume acquisition sequences. The ROI for tracking diaphragmatic motion was placed over the right diaphragmatic crus, with one third of the ROI positioned in the lung and two thirds in the liver (Fig. 1.).

Cardiac magnetic resonance and blood flow measurements

Cardiac MRI was performed in a three Tesla unit (Philips Ingenia 3T with dStream body coil Solution, Philips AG; Zurich, Switzerland). A board-certified radiologist was responsible for sequence planning and aligning stacks (MD). A standard three plane localizer and VCG-gated 2D PC CMR accelerated with k-t SENSE (TE: 2.9 ms; TR: 4.7 ms; SENSE: yes; slice thickness: 8 mm; slice gap: 5 mm; FOV: 180x180; Flip angle 10°;) were acquired in AV, PV, MV and TV planes, perpendicular to the flow direction. The peak velocity-encoding value (Venc) was set at 200 cm/s for all valves.

The DICOM images of the 2D PC CMR were analyzed on an extended workstation (Extended work space Philips AG; Zurich, Switzerland) with a compatible software (Cardiac Explorer and Q-FlowAnalysis Philips AG; Zurich, Switzerland). A board certified veterinary radiologist (MD) analyzed the 2D PC CMR studies by outlining the region of interest, such as the vascular lumen at the valve region manually and the respective blood flow was calculated automatically.

Two different PPU-gated 4D flow CMR (TE: 1.4 ms; TR: 4.6 ms;; slice thickness: 1.5 mm; slice gap: 0.8 mm; FOV: 200x220; Flip angle 20°) were obtained. Acceleration was performed once by k-t SENSE (acceleration factor of 3) and once by k-t BLAST (6-fold acceleration). Retrospective gating divided the cardiac cycle in 24 phases.

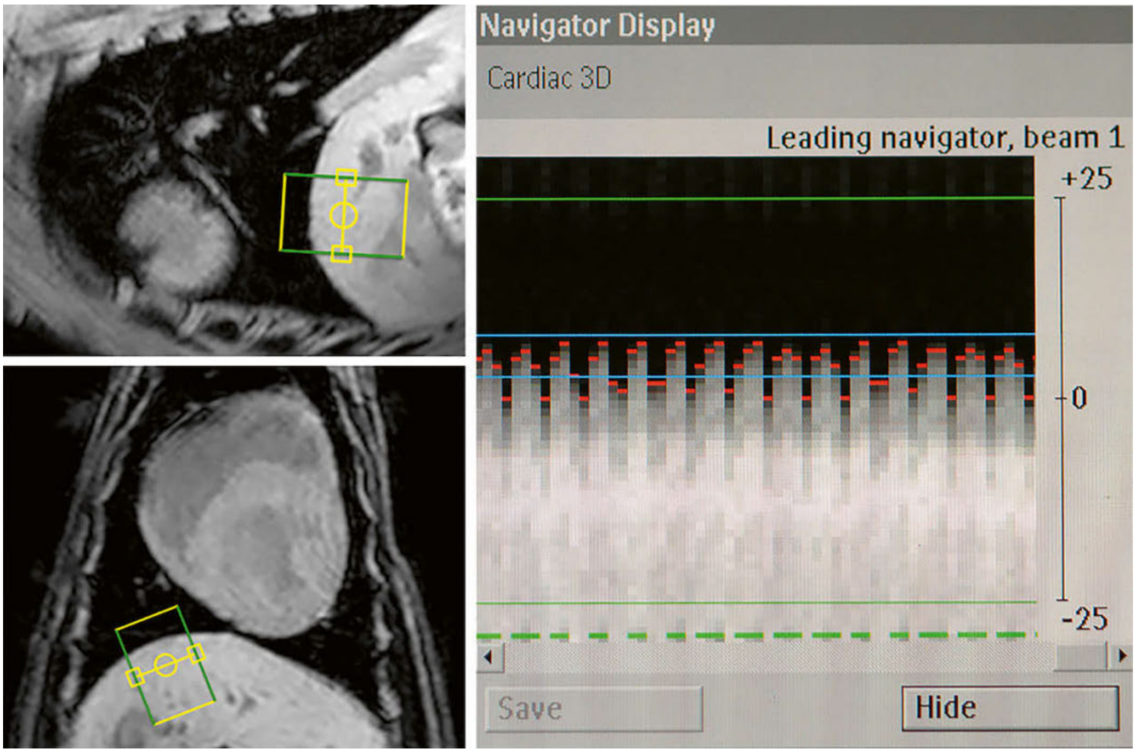

Figure 1: Respiration navigation. Respiration navigation was used in the 4D flow CMR. The ROI for tracking diaphragmatic position was placed over the right diaphragmatic crus, with one third of the ROI located in the thorax and two thirds in the abdomen. Rejection of measurements, acquired during diaphragmatic displacement, eliminates respiratory motion artifacts.

The cine images (magnitude and velocity images) of both accelerated sequences were implemented as a separate module in a commercially available GTFlow software (GyroTools LLC, Zurich, Switzerland) and analyzed by a resident of veterinary diagnostic imaging (NSP). (Fig. 2 and Fig. 3)

The measurement plane was set perpendicular to the flow direction at AV and PV and the atrioventricular valves and a ROI was manually drawn in the velocity-encoded maps outlining the lumen of the vessel in all 24 segments of the cardiac cycle. The software generated automatically a time velocity curve shown as graph and calculated the stroke volume at the specific localization.

Statistical analysis

The statistical analyses were performed by one of the co-authors (HR) using SPSS (IBM SPSS Statistics for Windows, version 21.0, IBM Corp. Armonk, NY, USA). Due to the small number of animals, the data were analyzed as non-parametric with a Friedman test across multiple measurements, followed by a Wilcoxon Signed Ranks Test between two repeated measurements. The level of significance was set at $p < 0.05$.

Table 1: Mean, standard deviation, minimum and maximum values of the stroke volume measured with the 2D PC CMR accelerated with k-t SENSE and the 4D flow CMR accelerated with k-t SENSE and k-t BLAST at the four cardiac valves of seven healthy beagle dogs.

		2D k-t SENSE (ml/beat)	4D k-t SENSE (ml/beat)	4D k-t BLAST (ml/beat)
Aortic valve	Mean ± StdDev	15.59 ± 3.56	15.43 ± 5.05	8.57 ± 1.91
	Min	12.5	11.1	5.6
	Max	22.7	25.1	10.8
Pulmonic valve	Mean ± StdDev	16.01 ± 3.40	13.06 ± 2.93	7.61 ± 1.67
	Min	11.8	9.9	4.8
	Max	22.8	18.9	10.1
Mitral valve	Mean ± StdDev	15.71 ± 4.17	14.56 ± 4.57	11.29 ± 3.01
	Min	11.8	10.3	5.6
	Max	23.6	21.9	15.1
Tricuspid valve	Mean ± StdDev	15.21 ± 2.89	11.53 ± 3.61	8.57 ± 4.04
	Min	11	6.4	1.2
	Max	18.4	17.8	12.9

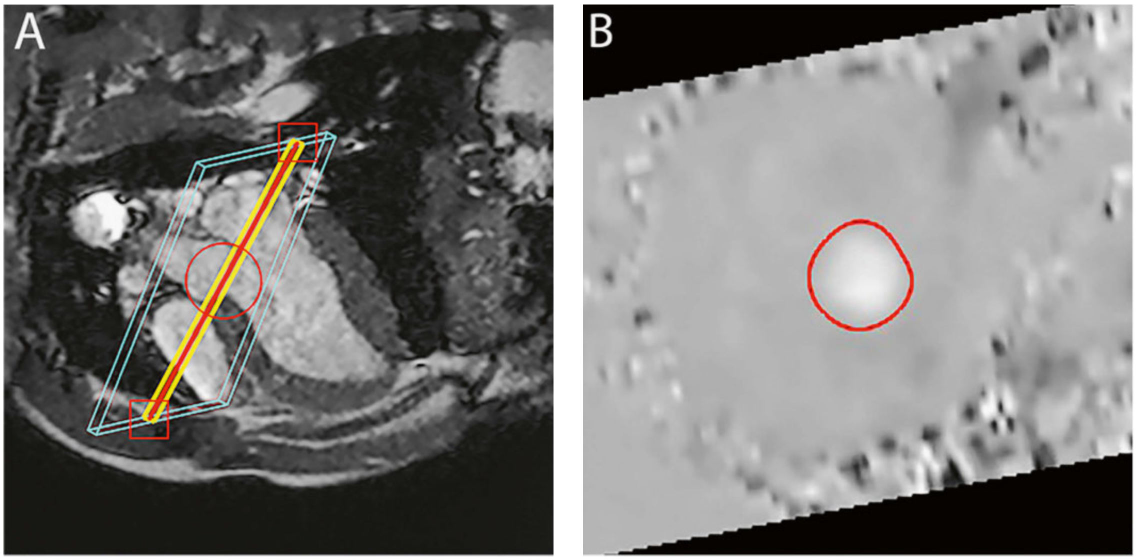

Figure 2: A: Sagittal plane of a canine heart using a time-resolved phase contrast sequence, B: associated velocity-encoding map outlining the aortic volume at the level of the aortic valves.
The stack is positioned with a short distance to the aortic valve (AV) using the sagittal plane. The ROI is manually drawn on the velocity-encoding map outlining the vascular lumen. The software (GyroTools LLC, Zurich, Switzerland) expressed the stroke volume automatically.

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Results

The seven Beagle dogs were considered healthy based on normal cardiac function and cardiac morphology examined by echocardiography and blood values within normal ranges. During the MRI examination, the systolic and diastolic blood pressure (BP) as well as the heart rate were always within physiologic ranges (BP: MAP > 60 mmHg, HR: 70 – 120 beats per minute).

Stroke volume assessed using the 2D PC CMR acquired under breath-hold for AV, PV, TV and MV revealed 15.59 ± 3.56 ml, 16.01± 3.40 ml, 15.21 ± 2.89 ml and 15.71 ± 4.17 ml. The 4D flow CMR k-t SENSE with respiration navigation resulted in stroke volume of 15.43 ± 5.05 ml, 13.06 ± 2.93 ml, 11.53 ± 3.61 ml and 14.56 ± 4.57 ml at AV, PV, TV and MV and the 4D flow CMR accelerated with k-t BLAST at the same locations 8.57 ± 1.91 ml, 7.61 ± 1.67 ml, 8.57 ± 4.04 ml and 11.29 ± 3.01 ml. The results measured using the three different methods are summarized in Table 1.

A comparison of measurements across multiple acquisition and acceleration techniques revealed significant differences of stroke volume at 3 localizations determined by Friedman Test (AV: $p = 0.004$, PV: $p = 0.002$ and TV: $p = 0.001$). No significant differences occurred by Friedman Test at MV ($p = 0.156$). The observed differences at AV, PV and TV were further analyzed and confirmed using the Wilcoxon Signed Rank Test. AV

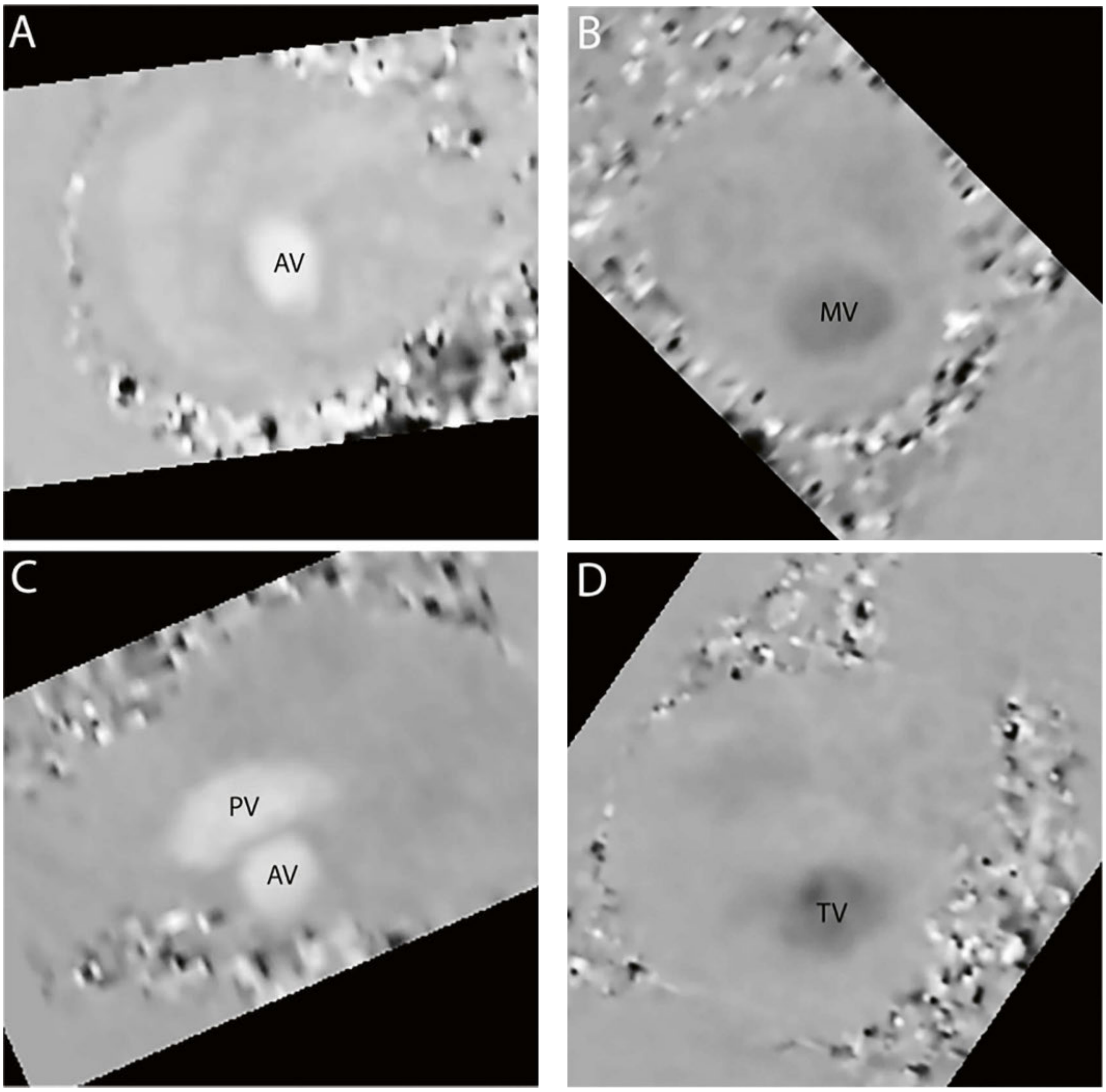

Figure 3: Velocity-encoding maps (cm/s) acquired by a 4D flow CMR. A: aortic valve (AV), B: mitral valve (MV), C: aortic and pulmonic valve (AV and PV), D: tricuspid valve (TV).
The positive through plane flow (AV and PV) is shown as bright areas and the negative through plane flow as dark areas (MV and TV) within a grey map of static tissue (myocardium).

showed no significant differences comparing the 2D PC CMR k-t SENSE sequence and the 4D flow CMR k-t SENSE (p = 0.31). Differences were significant when comparing the 2D PC CMR k-t SENSE and the 4D flow CMR k-t SENSE at PV (p = 0.028) and TV (p = 0.018) and comparing both methods with the 4D flow CMR k-t BLAST at AV, PV and TV (p = 0.018 for all localizations).

Discussion

The 4D flow CMR was introduced in veterinary medicine to evaluate the stroke volume at all cardiac valves. To the author's knowledge, assessment of stroke volume was not yet performed by a 4D flow CMR in healthy dogs. The volume acquisition CMR of the heart was recently used in studies of Mai et al. (2010) and Lee at al. (2017) to assess cardiac morphology and to perform a contrast-enhanced angiography of the great vessels. The hypothesis that no significant differences occur between stroke volume measured with different methods in variable locations, had to be rejected partially. On the left side of the heart, MV showed no significant differences comparing all three methods. However, on the right side of the heart, measured at PV and TV, significant differences in stroke volume between all three different methods of data acquisition could be detected.

Guidelines for ROI placement within the great cardiac vessels have been published in human medicine (Lotz et al., 2002). Therefore, the ROI within the aorta was not placed exactly at the aortic valve to prevent turbulent flow caused by valve movements and the ROI to measure the pulmonic flow was set between the pulmonic valve and the pulmonic bifurcation. Setting the planes in 2D PC CMR as well as positioning the stack for in the 4D flow CMR turned out to be more challenging in the PV and TV due to their anatomic localization and bent course. If the planes using a 2D PC CMR are not correctly positioned the entire sequence has to be repeated, making the acquisition period more time consuming and hence resulting in prolonged anesthesia. The main advantage of the 4D flow CMR is to include the whole heart and the adjacent vessels within the field of view (FOV) and the desired imaging planes can be reconstructed after acquisition, reducing the necessity of repeating sequences due to mal-positioning of planes. After placement of the stack in the 4D flow CMR images, the ROI was drawn within the velocity-encoding map outlining the vascular lumen, which was easiest to perform for AV and PV due to sharp contours of the vascular lumen and less overlap with each other. The atrioventricular valves revealed a less precise area of flow and were partially superimposed by the aorta and pulmonary artery. Therefore, ROIs at all 24 segments per cardiac cycle for all cardiac valves were drawn manually to prevent flow measurement failures due to incoming flow from another vessel.

In general, the values of stroke volume measured at the four cardiac valves performed with the 4D flow CMR accelerated with k-t SENSE were mildly lower than in 2D PC CMR k-t SENSE, which is in consensus with studies published in human medicine (Carlsson et al., 2011). Furthermore, in that study no significant differences in stroke volume measured at the aorta and main pulmonary artery were found when comparing the 4D flow CMR accelerated with k-t SENSE and the 2D PC CMR k-t SENSE sequence. The values of stroke volume in this study did show a low standard deviation in all sequences and the values measured in 2D PC CMR k-t SENSE and 4D flow CMR k-t SENSE were comparable with other studies measuring stroke volume by cardiac MRI in dogs of similar size (Hockings et al., 2003; Kim et al., 2013; Meyer et al., 2013; Sieslack et al., 2013; Sieslack et al., 2014; Drees et al., 2015; Drees et al., 2015).

The acceleration with k-t BLAST showed the lowest values of stroke volume in comparison with the methods accelerated by k-t SENSE. This is in consensus with previous studies applied in human medicine, which could show temporal blurring with k-t BLAST acceleration for stroke volume (Stadlbauer et al., 2009; Stadlbauer et al., 2010; Carlsson et al., 2011; van Ooij et al., 2013). This effect can be explained, as stroke volume is the sum of flow volumes over all heart phases. Other flow measurements, which are averaged over time, are not sensitive to temporal blurring, such as e.g. mean velocity. In human studies, additional acceleration methods were used and in a recent study EPI (echo-planar-imaging) was shown to be more stable for assessment of intra-cardiac flow measurements than k-t-SENSE and k-t-BLAST (Garg et al., 2017). Brix et al. compared the conventional 2D PC CMR with a 4D flow CMR accelerated with EPI (echo-planar-imaging) at the ascending aorta and the main pulmonary artery and no significant differences were seen. To prevent prolonging the time the animals are under anesthesia further measurements with additional acceleration techniques were avoided in this study.

An additional advantage of the 4D flow CMR was the independence of breath-hold technique. The animals could breath continuously, in our study under controlled ventilation, with a CO_2 level in a physiological range. The dogs in our study obtained positive pressure ventilation with adaptation of the respiratory rate to achieve a physiologic end-tidal carbon dioxide ($PE'CO_2$) of 40 mmHg (5.3 kPa), which was kept constant during acquisition with respiration navigation. Respiration nav-

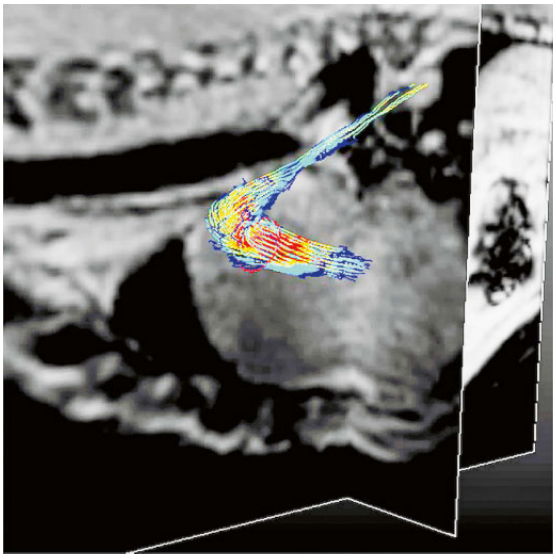

Figure 4: 3D image of the heart performed by a 4D flow CMR presenting flow through the aortic valve, plotted as streamlines.

igation is an advantage for clinical patients, especially if they have cardiac function deficits.

For breath-hold, applied during the acquisition of the 2D PC CMR, the dogs were first hyperventilated (by increasing the respiratory rate, not the tidal volume) to reduce PE'CO2 to 35 mmHg (4.7 kPa). Then, expiratory apnea was induced by switching off the ventilator for the duration of the image acquisition of a single slice (5-30 seconds). This led to constantly increasing PaCO2 values during apnea leading to PE'CO2 of 40-50 mmHg (5.9-6.6 kPa) when resuming ventilation. The positive correlation of CO2 and stroke volume within the physiologic range (Hedenstierna and Löfström, 1973) could have an influence on stroke volume depending on the PaCO2 level at the moment of sequencing, meaning a rather low stroke volume when directly starting at the beginning of breath holding and a rather higher stroke volume at the end of breath holding. Since MRI sequences average multiple heartbeats over the entire length of the acquisition, this influence is minimized.

The main limitation of the study is the low number of animals. The statistical power could not be assessed in advance, since these are the first results comparing the 2D PC CMR and 4D flow CMR in dogs. The limited number of included animals has a direct effect on the quality of the available result. Based on this first information, it would be beneficial to start a clinical study including a larger number of measurements. An additional limitation was the unequal distribution of male and female dogs as well as the inclusion of a single breed. The age distribution of our population did not represent the expected population of clinical patients.

Conclusion

4D flow CMR is a rapid and feasible method to evaluate cardiac function. The established method can be replaced with the volume acquisition SENSE for the left side of the heart. On the right side, significant differences are seen and studies with a larger number of animals are needed to clarify this finding. Acceleration image acquisition with k-t BLAST underestimates stroke in comparison to k-t SENSE and should be avoided for numeric quantification of flow parameters of examination. The main advantage using a 4D flow CMR is the independence of operator skills in placement of cardiac planes and the inclusion of the whole heart in the FOV as all imaging planes are acquired during a single acquisition reducing the time of general anesthesia of the animals. All desired measurements are postponed to post processing and performed after acquisition. This is an important point regarding clinical patients and especially patients with cardiac diseases, having a higher risk of complications during anesthesia.

The acquisition of the whole heart adding the time as the fourth dimension gives the advantage of visualization of flow plotted as streamlines (Fig. 4). The possibility of visualization of vascular flow in MRI opens the field of additional procedures and with the new technique a large amount of measurements, acquired with a single sequence, is possible.

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Mesures de flux par tomographie par résonnance magnétique en 4D dans le cœur de chiens en bonne santé

Lors d'examens cardiaques par résonnance magnétique (CMR), le plan pour des mesures de flux précises doit être défini perpendiculairement à la direction de flux sanguin. Dans la CMR en contraste de phases 2D (PC), le choix de ce plan se fait durant l'examen, ce qui prend du temps et peut être sujet à des problèmes. Avec la mesure de toutes les données relatives au flux sanguin dans l'ensemble du cœur au moyen d'un 4D flow CMR, on déplace le moment de ce choix dans la phase de traitement des données. La collecte d'une quantité aussi élevée de données nécessite une accélération de la technique de mesures comme par exemple SENSitivity Encoding (k-t SENSE) ou Broad-use Linear Acquisition Speed-up Technique (k-t BLAST). Le but de cette étude était de comparer la CMR 4D, accélérée avec deux méthodes différentes avec la CMR 2D bien établie, ceci sur la base de la détermination du volume d'éjection systolique au niveau des quatre valvules cardiaques. Les valeurs du volume d'éjection pour le cœur gauche (valvules aortiques et mitrales) obtenues par 4D flow CMR k-t SENSE n'étaient pas significativement différentes de celles obtenues par 2D PC CMR k-t SENSE. Par contre, des différences significatives entre les deux techniques étaient constatées au niveau des valvules pulmonaires et tricuspid. L'accélération par k-t-BLAST donnait de façon générale des valeurs du volume d'élection plus basses au niveau de toutes les valvules, à l'exception de la valvule mitrale.

Misure del flusso in 4D nel cuore in cani sani con l'ausilio della risonanza magnetica cardiaca

Al momento dell'esame cardiaco mediante risonanza magnetica (CRM) il piano per delle misure accurate del flusso deve venire definito in quanto perpendicolare alla direzione del flusso sanguigno. Già durante la CRM a contrasto di fase 2D (PC), la scelta del piano durante l'esame ha richiesto tempo ed è stata soggetta a problemi. Con la misura di tutte le informazioni del flusso sanguigno in tutto il cuore via una CRM con flusso 4D, la scelta del piano è passata ad un'elaborazione seguente. La raccolta di tali grandi quantità di dati richiede un'accelerazione della tecnica di misura quale SENSitivity Encoding (k-t SENSE) oppure Broad-use Linear Acquisition Speed-up Technique (k-t BLAST). Scopo di questo studio era di paragonare il flusso 4D della CRM, accelerato con due diversi metodi, e con la riconosciuta 2D PC CRM sulla base della determinazione dei volumi di gittata su tutte e quattro le valvole cardiache. I valori della misurazione della gittata nella parte sinistra del cuore (valvola aortica e mitrale), misurati via la CRM a flusso 4D con k-t SENSE erano significativamente differenti rispetto alle misurazioni mediante il k-t SENSE per il 2D PC CRM. Per quel che riguarda la valvola polmonare e la tricuspide si sono riscontrate differenze significative tra queste due tecniche. L'accelerazione via k-t -BLAST ha rivelato in generale valori inferiori del volume di gittata per tutte le valvole cardiache eccetto la valvola mitralica.

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Corresponding author

Nadia S. Pfammatter
Clinic of Diagnostic Imaging
Vetsuisse Faculty Zurich
Winterthurerstrasse 258c
CH-8057 Zurich
Tel: +41 44 63 59126
Fax: +41 44 63 58940
E-Mail: npfammatter@vetclinics.uzh.ch