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ECG-GATED CARDIAC MULTIDETECTOR CT EVALUATION OF THE NORMAL PULMONARY VALVE AND RIGHT VENTRICULAR OUTFLOW TRACT IN DOGS

ABSTRACT

With the advancement in imaging technology, ECG-gated cardiac multidetector computed tomography (MDCT) has emerged as a tool for the anatomic evaluation of the pulmonary valve and right ventricular outflow tract (RVOT) in human medicine[1.] Currently, the evaluation of the pulmonary valve relies primarily on echocardiographic examination. However, the bidimensional nature of this technique and the location/orientation of the pulmonary valve in the thoracic cavity can pose challenges.[2,3] In human medicine, ECG-gated MDCT distinguishes four main anatomic components of the pulmonary valve and RVOT: the pulmonary valve leaflets, the sinotubular junction, the anatomic ventriculo-arterial junction and the hemodynamic ventriculo-arterial junction[1]. Hence, the aim of this study was to describe the computed tomographic findings of the normal RVOT and pulmonary cusps in a population of dogs.

This is an anatomic prospective descriptive study. A total of 24 dogs were included that underwent a complete echocardiographic examination and an ECG-gated MDCT to rule out pulmonary valve abnormalities. Multiplanar reconstruction of the pulmonary valve was obtained. Additionally, hearts from three dogs euthanized for reasons unrelated to the study were collected and their gross and histological findings were compared to the CT images. ECG-gated MDCT provided good visualization of the pulmonary valve leaflets, the sinotubular junction, the anatomic ventriculo-arterial junction and the hemodynamic ventriculo-arterial junction. Notably, the short-axis view of the pulmonary valve anatomy resembled the 'Mercedes-Benz sign' characteristic of the aortic valve in all dogs. In conclusion, this study provides the first description of the CT anatomy of the RVOT in dogs without pulmonary valve and RVOT abnormalities.

INTRODUCTION

ECG-gated cardiac multidetector computed tomography (MDCT) has emerged as a valuable tool for the anatomic evaluation and assessment of the pulmonary valve and right ventricular outflow tract (RVOT) in human medicine.[1] In veterinary medicine the evaluation of the pulmonary valve relies primarily on echocardiographic examination; however, the bidimensional nature of the echocardiographic examination and the location/orientation of the pulmonary valve in the thoracic cavity can pose challenges for a thorough exploration of this vascular structure. This challenge is particularly evident in brachycephalic dogs, where a narrow/insufficient acoustic window sometimes leads to inaccuracies in echocardiographic examination.[2]

In human medicine, ECG-gated MDCT commonly distinguishes four main anatomic components of the pulmonary valve and right ventricular outflow tract (RVOT): the pulmonary valve leaflets, the sinotubular junction, the anatomic ventriculo-arterial junction and the hemodynamic ventriculo-arterial junction.[1,4,5]

According to the current literature, there are no reports describing whether these four components can also be observed and distinguished in dogs and, if so, to what extent.

Therefore, the aim of this study is to describe the computed tomographic findings of the RVOT and pulmonary valve leaflets in a population of dogs without pulmonary valve and RVOT abnormalities.

MATERIAL AND METHODS

This is an anatomic prospective descriptive study conducted at XXXX and XXXX from January 2022 to January 2023. Owner consent was obtained before enrollment in the study and an institutional ethical approval was obtained before the study commenced. Inclusion criteria comprised dogs with different cardiac and systemic pathologies (Table 1) that underwent a complete echocardiographic examination to exclude pulmonary valve abnormalities and subsequently underwent an ECG-gated MDCT. Dogs with thoracic or cardiac pathologies that might alter the morphology of the pulmonary valve and RVOT and those without a complete echocardiographic examination prior to CT were excluded. All examinations were conducted using a 64-MDCT unit (64-MDCT Lightspeed, General Electric Medical System,XXXX). Following pre-anaesthetic assessment, dogs received intramuscular treatment with 0.3 Fentanyl µg/kg (Fentandon 50µg/ml Dechra, XXXX), 0.2 mg/kg Methadone (Semfortan 10mg/ml, Dechra, XXXX) and 0.2 mg/kg Midazolam (Midazolam Hameln 5mg/ml, Hameln Pharma, XXXX). General anesthesia was induced and maintained with Propofol (Proposure 10mg/ml, Boehringer Ingelheim, XXXX) and Isoflurane (IsoFlo, Zoetis, XXXX). In cases where the heart rate (HR) exceeded 100 beats per minute, a 0.3 µg/kg bolus of dexmedetomidine (Dexdomitor 0,5mg/ml, Orion Pharma, XXXX) was administered intravenously to reduce the HR. Dogs were prepared for ECG-gated MDCT as previously described[6], and a pre-contrast scan of the thorax was performed. Intravenously 2 mL/kg of iodinated nonionic contrast medium (Omnipaque 350mgI/ml, GE Healthcare, XXXX) was administered at a flow rate of 3 mL/s using a double-head power injector system followed by 4 ml of saline infusion at the same flow rate. The contrast bolus-tracking technique was employed to determine the starting delay, with a region of interest drawn within the lumen of the brachiocephalic vein ipsilateral to the cephalic vein catheter.

Helical retrospective ECG-gated scanning parameters were set at 100-120 kV, 350 mA, 0.35-s tube rotation time, and HR-adapted variable pitch, with the field of view centered on the heart and set as small as possible to include its entire profile. Apnea was induced and maintained using a mechanical breath holder. The CT images were retrospectively reconstructed at the late-diastole (75% of the R-R interval) as indicated in literature.[6]

A multiplanar reconstruction of the pulmonary valve and RVOT using a DICOM viewer software (HorosDICOM viewer, www.horosproject.org) was obtained, and all images were reviewed by a second-year radiology resident and a board-certified veterinary radiologist. Following the anatomic human classification[1], a CT classification of the hemodynamic, anatomic, and sinotubular junction regions of the main pulmonary artery was proposed including the assessment of valvular cusps identification (Figure 1 and 2). According to the anatomical classification described in human studies, the hemodynamic junction refers to the semilunar fibrous attachments of the leaflets to the wall, corresponding to the pulmonary "annulus".[1,4,5] This junction is the most proximal component of the RVOT and can be visualized in CT as a small narrowing that separates the right ventricle from the valve. The anatomic junction corresponds to the union between the muscular infundibulum of the ventricle and the arterial wall of the pulmonary trunk crossing the entire valvular block. [1,4,5] The sinotubular junction corresponds to the distal part of the sinuses, separating the pulmonary valvular sinuses from the tubular component of the pulmonary trunk.[1,4,5] It constitutes the most distal component of the pulmonary valve and, in CT, is visualized as the narrowing that separate the pulmonary valve from the pulmonary arterial trunk.

A qualitative visualization score ranging from 0 to 2 was assigned to each of the four main anatomic components, with 0 indicating not visible, 1 for barely visible, and 2 for good/excellent visualization. Both observers independently scored each component in all the CT exams included in the study, with any discrepancies resolved through consensus.

Three canine hearts were obtained from dogs euthanized for reasons unrelated to the study within 24H from the CT study.

The hearts were promptly removed from the thoracic cavity and preserved in formalin. Macroscopic examination involved dorsal observation of the valve at the arterial aspect. Subsequently, the entire right outflow tract was investigated through a longitudinal opening, encompassing the muscular part of the infundibulum, the valve, and the pulmonary artery. The three components of the right ventricular outflow and pulmonary root were visualized after removal of the lateral portion of the infundibulum with the intermediate pulmonary cusp. Gross and histological findings from these examinations served as a basis for comparison with the CT images.

RESULTS

Initially, twenty-eight dogs were considered for inclusion in this study. However, one dog (3,7%) and three dogs (10,7%) were excluded due to ventricular arrhythmias during general anesthesia, resulting in poor spatial and contrast resolution of the CT images, and technical issues with the archive, respectively. Consequently, 24 dogs were included in the final analysis, comprising 9 neutered males, 9 spayed females, 3 intact females, and 3 intact males. The median age was 10.5 (min-max 3-14 years). Among the dog breeds, there were 1 American Staffordshire, 1 Czechoslovakian Wolfdog, 1 Dogue de Bordeaux, 2 English bulldogs, 1 English Setter, 3 French Bouledogues, 1 Golden Retriever, 1 Irish Setter, 1 Jack Russell Terrier, 1 Japanese Akita, 1 Miniature Pinscher, 8 mix breed, 1 Springer Spaniel and 1 West Highlands White Terrier.

Three dogs had no detected cardiac abnormalities. The remaining cases presented various cardiac abnormalities (Table 1). Heart rate was maintained below 100 beats/minute in all dogs using drug administration when necessary as previously indicated.

The hemodynamic junction received a score of 2 in 21 out of 24 dogs (88%) and a score of 1 in 3 out of 24 dogs (12%). None of the dogs received a score of 0. The anatomic junction received a score of 2 in 18 out of 24 dogs (75%), a score of 1 in 5 out of 24 dogs (21%), and a score of 0 in 1 out of 24 dogs (4%). The sinotubular junction received a score of 2 in 22 out of 24 dogs (92%) and a score of 1 in 2 out of 24 dogs (8%). None of the dogs received a score of 0.

The visualization of the valve leaflets received a score of 2 in 21 out of 24 dogs (88%), a score of 1 in 2 out of 24 dogs (8%), and a score of 0 in 1 out of 24 dogs (4%).

In the hearts collected from the dogs of the study euthanised, the three components of the right ventricular outflow and pulmonary root were successfully visualised and used as a comparison for the CT images.

DISCUSSION

The use of ECG-gated MDCT in veterinary medicine is fairly recent. [3,6,10,12] The primary rationale for using the gating of CT scans during the cardiac cycle is the reduction of motion artifacts, contributing to improved delineation of structures and more accurate measurements. [9,] In veterinary practice, non-gated CTAs are more prevalent, as ECG-gating involves additional software that adds to the cost of purchasing a CT scanner.[10,11,20] The lack of gating, particularly in the presence of fast-moving anatomical structures like the pulmonary valve leaflets, can pose challenges in precisely measuring landmarks, potentially resulting in inaccuracies.[11]

Presently, echocardiography is the primary imaging modality for characterizing cardiac structure and function in animals. Nevertheless, cardiac ultrasonography has its limitations, mainly due to narrow acoustic windows and its predominant reliance on a 2-dimensional approach. Moreover, its effectiveness is strongly dependent on the operator's skill, available acoustic windows, and heart shape.[12,18,21;22;26]

Multidetector CT, especially ECG-gated one, effectively overcomes these limitations since it is not impeded by air or bone interfaces. Modern scanners can now achieve exceptional spatial and temporal resolution, even in small animal.[12,25,26.]

In this study, ECG-gated MDCT provided good to excellent visualization of the four components of the right ventricular outflow tract (RVOT), typically distinguished in humans, in all cases for the hemodynamic and sinotubular junctions, in 96% of cases for the pulmonary valve leaflets, and in 75% of cases for the anatomic junction. Among the different regions studied, the anatomic junction exhibited the lowest quality and quantity of visibility in our study. We postulated that this observation could be attributed to its extensive nature, unlike the other components. The anatomic junction represents the connection between the ventricle and the arterial wall, traversing almost the entire valvular region. This intricate arrangement may pose challenges in identifying it as a distinct and well-defined structure in CT images. In humans, a thorough comprehension of the anatomy of the normal right ventricular outflow junctions is essential for the systematic analysis of all lesions affecting the outflow tract, facilitating a more precise description and classification of such lesions.[13,19,23,25]

The pulmonary valve consists of right, left, and intermediate semilunar cusps.[15]. In human medicine, the nomenclature for pulmonary valve leaflets varies based on their spatial position in the thorax or their relation to the aortic sinuses.[1,19,24] In veterinary medicine, according to the Veterinary *Nomina Anatomica* [28] the two most cranial cusps are the right and intermediate, situated to the right and to the left, respectively, while the most caudo-ventral one is the left. These names align with the position of the aortic sinuses. While specific literature data regarding the nomenclature of pulmonary cusps in veterinary medicine are lacking, we presume that it is derived from their spatial relationship with the aortic sinuses. During CT multiplanar reconstruction of the RVOT and alignment along the axis of the pulmonary valve, it is evident that the intermediate and left cusps names don't correspond to their real spatial position (with the left cusp situated caudally and the intermediate cranio-laterally to the left).

In human medicine, the spatial and anatomical (that is in relation to the aortic sinuses) nomenclature of the cusps is used interchangeably. Introducing a nomenclature for pulmonary cusps based on their spatial position could be helpful in veterinary medicine, particularly when examining the pulmonary valve tomographically (Fig 4).

In addition, the pulmonary valve and the aortic valve exhibit similar anatomic components and are both classified as semilunar valves. [16] In dogs, the normal appearance of the aortic valve on transthoracic echocardiography resembles an inverted "Mercedes-Benz sign" or "Y" shape, formed by the three aortic valve cusps during diastole.[17-18] Interestingly, according to the current literature there are no echocardiographic reports detailing this specific feature for the pulmonary valve likely due to to the difficulty in obtaining the transverse axis of the pulmonary valve with standard echocardiographic windows.[18] CT multiplanar reconstructions allows to obtain a transverse section of the pulmonary valve revealing a distinct "Mercedes Benz sign" appearance very similar to that observed for the aortic valve (Figure 3). Therefore, ECG-gated MDCT enabled effective visualization of the pulmonary leaflets. In the traditional MDCT, the pulmonic cusps tend to be faint[14], primarily due to pulsatility artifacts and inadequate spatial resolution. ECG-gated MDCT, with its superior spatial resolution, facilitates the cross-sectional characterization of small anatomical structures, such as the pulmonary valve leaflets.[10]

Two major factors affecting the quality of ECG-gated MDCT are the presence of tachycardia and arrhythmias, which generally degrade image quality due to the inherent limitations of the technology. Although newer generations of scanners and reconstruction algorithms can partially mitigate the effects of high heart rates and irregular rhythms, maintaining a low and regular heart rate remains critical for optimal image quality in cardiac CT..[12] There are two types of ECG gating, retrospective and prospective, which differ in the duration the x-ray tube remains active during the cardiac cycle. In retrospective gating, the CT tube is active throughout the entire cardiac cycle, whereas in prospective gating, image acquisition occurs only during a selected phase of the cardiac cycle.[6,12]

ECG-gated scans can be acquired or reconstructed at different points in the cardiac cycle, depending on the study's purpose and the structures of interest.[6,12] For instance, in coronary studies or single-phase assessments, a late or end-diastolic phase, or sometimes an end-systolic phase, is often sufficient. In contrast, functional studies, which involve retrospective gating of the full cardiac cycle, are necessary when evaluating dynamic changes in cardiac structures or functions. Typically, ECG-gated scans are acquired or reconstructed when cardiac motion is minimal, such as in mid-to-late diastole or end-systole.[6,12] For this reason, a regular and consistent rhythm and a low heart rate will result in the best image quality. A regular heart rhythm allows the scanner to accurately reconstruct the images in the chosen RR interval or to predict when the next R wave will occur and results in the same phase of the cardiac cycle occurring at a consistent interval after each detected R wave.[12] In this study the presence of arrhythmias and tachycardia was the main cause of poor or non visualisation of the components of the RVOT and pulmonary cusps leading to motion artifacts and blurry images.

This study has several limitations. Firstly, most of the patients presented a different clinical status at the time of anesthesia and only three patients had no cardiac pathology at the time of CT. The presence of tachycardia or arrhythmias leads generally to a worsening of the quality of the ECG-gated CT studies. Poor or impossible visualization of the RVOT components was attributed to irregular heartbeat/high HR during anesthesia, resulting in motion artifacts superimposed on the pulmonary valve in 2 out of 24 cases, and/or the presence of an extra-cardiac mass partially compressing the pulmonary valve in 1 out of 24 cases.

Finally, the heterogeneous population may have led to a different visualization of the RVOT components and pulmonary cusps. Subsequent studies are necessary to evaluate whether these components can be better visualized in some breeds than in others or in brachycephalic dogs compared to non-brachycephalic dogs.

In conclusion, this study provides the first description of the CT anatomy of the RVOT in dogs without pulmonary valve and RVOT abnormalities. A comprehensive understanding of the CT anatomy of the normal RVOT is crucial for future investigations involving dogs with pathologies affecting the pulmonary valve.

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TABLES

TABLE 1. Signalment, anamnesis and tomographic diagnosis of the 24 dog enrolled in the study.

PATIENT NUMBER	BREED	AGE (years)	SEX	ANAMNESIS	TOMOGRAPHIC DIAGNOSIS
1	Amstaff	12	SF	Arrhythmia and suspected neoformation of the cardiac base at the echocardiography	Nodular lesion at the heart base
2	Czechoslovakian wolfdog	14	NM	Cardiac mass at the echocardiographic examination	Nodular lesion at the heart base
3	Dogue de Bordeaux	8	SF	Cardiac tamponade 24 hours earlier	Expansive lesion of the right auricle
4	English bulldog	9	NM	Cardiac tamponade one week earlier	Suspected clot identified between the emergence of the pulmonary trunk and the cranial profile of the left atrium

5	English bulldog	5	SF	Suspected cardiac mass at the echocardiographic examination	No cardiac anomalies observed
6	English setter	13	M	Cardiac tamponade 24 hours earlier	Infiltrative lesion of the right atrium associated with moderate pericardial effusion
7	French bouledo gue	5	SF	Loss of appetite, cough, increased respiratory rate	Endoluminal expansive lesion protruding into the left atrium
8	French bouledo gue	10	M	Cardiac mass at the echocardiographic examination	Nodular lesion at the heart base
9	French bouledo gue	13	M	Dyspnea/polypnea	Nodular lesion at the heart base
10	Golden retriever	9	SF	Cardiac tamponade 24 hours earlier	Mild pericardial effusion. No evidence of expansive cardiac lesion
11	Irish setter	9	SF	Cardiac tamponade 24 hours earlier	Mild pericardial effusion (pyopericardium in anamnesis)

12	Jack Russell	11	NM	Weight loss, loss of appetite	Multiple nodular lesions infiltrating the pericardial sac associated with mild/moderate pericardial effusion
13	Japanes e Akita	6	F	Hemopericardium	Infiltrative lesion of the right auricle
14	Miniatur e pinscher	3	M	Cardiac tamponade 24 hours earlier	Infiltrative lesion of the right auricle associated with mild pericardial effusion
15	Mix breed	11	NM	Pericardial effusion a week earlier at the echocardiografic examination	No cardiac anomalies noted
16	Mix breed	6	SF	Cardiac tamponade documented 24 hours earlier	Multiple pericardial nodules associated with mild pericardial effusion
17	Mix breed	12	NM	Cardiac mass at the echocardiography	Nodular lesion at the heart base
18	Mix breed	13	M	Cardiac mass at the echocardiography	Left myocardial expansile lesion

19	Mix breed	5	F	Suspected PDA at the echocardiography	Atypical morphology of patent ductus arteriosus of Botallo with secondary left-right aorto-pulmonary shunts
20	Mix breed	14	SF	Cardiac tamponade documented one week earlier	Infiltrative lesion of the right auricle associated with mild pericardial effusion
21	Mix breed	12	M	Cardiac tamponade documented 3 days earlier	Nodular lesion at the heart base
22	Mix breed	14	M	Cardiac tamponade documented 24 hours earlier	Infiltrative lesion of the wall of the right auricle
23	Springer Spaniel	10	F	Mild pericardial and pleural effusion	No cardiac anomalies noted
24	West Highlands White Terrier	11	SF	Dyspnea	Nodular lesion at the heart base

FIGURE LEGENDS

FIGURE 1

Photograph of the dorsal oblique view of the gross anatomy of the heart at the level of the atrio-ventricular junction in a 15-year-old mixed breed dog (case no. 15). 1: Intermediate pulmonary cusp. 2: Right pulmonary cusp. 3: Left pulmonary cusp. Arrows indicate the sinutubular junction. 4: Pulmonary artery. 5: Ascending aorta. 6: Mitral valve. 7: Tricuspid valve. R: right. L: left. Cr: cranial. Cd: caudal.

FIGURE 2

A. Photograph of the gross anatomy of the left surface, right ventricular outflow track, and pulmonary root after removal of the lateral portion of the *infundibulum* with the intermediate pulmonary cusp in a 5-year-old English bulldog (case no. 5). B: Sagittal multiplanar reformatted image illustrating the right ventricular outflow track. In both images, the red line indicates the hemodynamic junction; dotted yellow lines indicate the anatomic junction; black line represents the sinotubular junction, and the black asterisk indicates the infundibular muscle.

FIGURE 3

A. Photograph of the gross anatomy of a dorsal view of the pulmonary valve after removal of the lateral wall of the infundibulus in a 10 year-old Springer Spaniel (case no. 23) illustrating the left pulmonary cusp (1), the right pulmonary cusp (2), and intermediate pulmonary cusp (3). Black arrows indicate sinotubular junction. B: Dorsal multiplanar reformatted image showing the pulmonary valve at the same level of the anatomic image. R: right. L: left. Cr: cranial. Cd: caudal.

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FIGURE 4

Dorsal multiplanar reformatted image of the pulmonary valve of the same dog of Figure 3. A, published anatomic point of view B, spatial point of view. R, right pulmonary cusp; I, Intermediate pulmonary cusp; L, left pulmonary cusp. The red double arrow indicates the switching between the names of the two cusps.