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Qualitative and Morphometric Characterization of Coronary Arteries in Canines (*Canis lupus familiaris*). A Direct Anatomical Study

Caracterización Cualitativa y Morfométrica de las Arterias Coronarias en Caninos (*Canis lupus familiaris*). Un Estudio Anatómico Directo

Iván A. Pineda-Betancurt[1]; Luis E. Ballesteros-Acuña[1] & Fabián A. Gómez-Torres[1]

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SUMMARY: Information on the coronary irrigation of canines is scarce despite its great importance in the context of comparative anatomy and its applications in veterinary medicine. The objective was to perform a qualitative and biometric characterization of the coronary arteries in canines. Using the vascular bed perfusion technique, semisynthetic resin (Palatal GP40L 80 % and styrene 20 %) was injected into the arterial beds of 30 hearts from deceased dogs in veterinary clinics, which were categorized by weight as follows: <10 kg; (10 - 19 kg; 20 - 29 kg; ≥30 kg. The left coronary artery presented a caliber of 3.25 mm, significantly larger than that of the right coronary artery (p=0.01). The left coronary artery was bifurcated in 22 (73.3 %) hearts and trifurcated in 8 (26.7 %). The paraconal interventricular branch terminated in 20 cases (66.7 %) in the posterior aspect of the left ventricle and in the 10 - 19 kg group the termination distance of this branch to the apex was 10.53 +/-4.46 mm. Anastomosis at the level of the cardiac apex between the paraconal interventricular branch and the subsinusal interventricular branch was recorded in 4 cases (13.3 %). The pattern of coronary dominance was left in the whole sample, with subtype II in 25 hearts (83.3 %) and subtype III in 5 cases (16.7 %). Myocardial bridges were visualized in 2 cases (6.7 %). The detailed description of the coronary arteries and their branches, as well as their morphometry, considering the weight ranges of the canines carried out in the present study allows us to identify the differences in this vasculature in each of the groups evaluated. These findings may contribute to the improvement of clinical and interventional management involved in the cardiology of the species.

KEY WORDS: Canines; Coronary irrigation; Left coronary artery; Right coronary artery; Coronary dominance.

INTRODUCTION

The dog's heart is irrigated by the left coronary artery (LCA) and right coronary artery (RCA) (Álvarez Ramírez & Cruz Martínez, 2011). The LCA originates from the left aortic sinus, with a length of 0.5 - 1.2 cm (Oliveira *et al*., 2010), after a short course it bifurcates giving origin to the paraconal interventricular branch (PIB) with a length of 6.9 cm (Oliveira *et al*., 2011) and the circumflex branch (CXB) (Longo Büll & Fernandes Boaro Martins, 2002; Auriemma *et al*., 2018). The PIB runs along the paraconal interventricular groove, ending at the level of the cardiac apex, from which the anterior septal branches and left and right ventricular branches emerge (Gómez *et al*., 2012). The length of the CXB is 3.3 - 7.69 cm (Suematsu *et al*., 2000; Álvarez Ramírez & Cruz Martínez, 2011; Auriemma *et al*., 2018). It initially courses through the left ventricular atrial groove, and upon approaching the crux cordis gives rise to the subsinusal interventricular branch (SIB) which has a length of 3.4 cm (Oliveira *et al*., 2010). From the CXB emerge the left atrial and left posterior ventricular branches, and the branch of the atrioventricular node (Suematsu *et al*., 2000). The trunk of the LCA in humans is divided into several forms: bifurcated (described as the most frequent), producing the anterior interventricular branch (AIB) and the CXB; trifurcated, producing AIB, CXB and a left diagonal branch (LDB), and tetrafurcated, producing AIB, CXB and two LDBs (Reig & Petit, 2004; Ballesteros & Ramírez, 2008; Spicer *et al*., 2015). The LCA in bovines is more developed than the right; it forms a unilateral or "left" vascularization and is responsible for generating the arterial branches that cross the paraconal interventricular groove (Martínez *et al*., 2010). The LCA originates at the free edge of the left aortic trunk, runs briefly between the left atrium and the origin of the pulmonary artery, and then reaches the upper part of the anterior atrioventricular groove where it divides into two

[1]Department of Basic Sciences. School of Medicine. Universidad Industrial de Santander, Cra 32 # 29-31. 68002. Bucaramanga, Colombia.

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branches, the PIB and the CXB (Martín Roldán & Blánquez Layunta, 1982; Deepak & Rao, 2010; Gómez-Torres *et al*., 2023). In the pigs, the LCA is the main vessel that provides irrigation to the heart. It arises from the left aortic sinus, extends to the left behind the pulmonary trunk and ends bifurcating into the PIB and the CXB. Occasionally, it trifurcates giving rise to the LDB, a characteristic that has been described in humans with a frequency of 9-55 % and in pigs in 20 % (Jordão *et al*., 1999; Sahni *et al*., 2008; Gómez & Ballesteros, 2014).

The RCA emerges from the right aortic sinus with a length of 1 - 7.2 cm (Oliveira *et al*., 2010, 2011) runs along the atrioventricular groove and ends near the cardiac cross. From the RCA emerges the branches of the sinoatrial node, right conus arteriosus, atrial, right ventricular and right marginal branches (Khvatov *et al*., 2023). In humans, the RCA emerges from the right aortic sinus and runs through the right atrioventricular groove between the right atrium and right ventricle to the acute margin. In the long configuration of the RCA after taking a trajectory in the atrioventricular groove it divides, near or at the level of the cardiac crux into the posterior interventricular branch (PIB) and the left retroventricular branch. The short configuration of RCA ends as a posterior branch of the right ventricle in 7-20 % (Baptista *et al*., 1989; Kalpana, 2003; Ballesteros *et al*., 2011). The origin of RCA in bovine is at the upper margin of the right aortic sinus, it runs through the right atrioventricular groove where it ends, without reaching the subsinusal interventricular groove (Martín Roldán & Blánquez Layunta, 1982). The RCA's branches are in the right atrium and the lower part of the right ventricle along its entire length. The sinoatrial node branch (SANB) also emerges from it (Deepak & Rao, 2010; Martínez *et al*., 2010). The RCA in pigs emerges from the homonymous aortic sinus and irrigates both the atrium and the right ventricle. It is divided into three segments: the first segment runs along the anterior surface of the atrioventricular groove, the second segment runs along the posterior aspect of the atrioventricular groove, and the third segment is formed by the branches of its bifurcation near the cardiac crux (Sahni *et al*., 2008; Gómez & Ballesteros, 2013; Dai *et al*., 2020).

The pattern of arterial irrigation in canine hearts differs from that observed in humans. Several studies report left coronary dominance in dogs (Bertho & Gagnon, 1964; Noestelthaller *et al*., 2007; Álvarez Ramírez & Cruz Martínez, 2011), characterized by the presence of a long CXB that runs along the atrioventricular groove, and at the level of the cardiac crux emits the SIB (Bertho & Gagnon, 1964; Oliveira *et al*., 2010; Auriemma *et al*., 2018). The variability of the species in relation to coronary dominance has importance for experimental studies of coronary occlusion; in the dog, they result in myocardial ischemia that involves the atrium and left ventricle, and partially the posterior wall of the right ventricle (Suematsu *et al*., 2000). The coronary arteries of the dog differ from those of human in two main features: the presence of a distinct and separate septal artery as a branch of the LCA, and the formation of the SIB on the left in all canine cases *versus* 20 % as reported in humans (Ballesteros & Ramírez, 2008; Ballesteros *et al*. 2011).

Anastomoses between coronary vessels in dogs have not been described in detail in previous studies, despite being considered a protective factor that prevents acute myocardial infarction (Bakst *et al*., 1954). Myocardial ischemia and infarction related to coronary artery disease can also be observed in dogs and cats (Driehuys *et al*., 1998).

Myocardial bridges (MBs) are anatomical expressions in which a segment of the coronary arteries dips into the myocardium for a variable length and then continues its subepicardial course. MBs have been observed in dogs with an incidence close to 30 % (Zechmeister, 1965; van Nie & Vincent, 1989; Yamaguchi *et al*., 1996; Tangkawattana *et al*., 1997). This morphological variation alters myocardial perfusion in severe cases and in events of high physiological demand, they have been linked as a cause of an acute myocardial event that can lead to death (Roberts *et al*., 2021).

In recent decades the clinical care of domestic dogs in the cardiological area has acquired great importance, due to their special condition as companion animals, and the fact that they are considered a viable species as an experimental model, however, little information has been reported on the detailed characteristics of the coronary circulation in this species. These studies have not accurately reported the trajectories, branches, lengths and calibers of the coronary circulation of dogs and their variations, which has meant that procedures such as coronary angiography and endovascular therapies for congenital or degenerative cardiac pathologies are in the process of development (Scansen, 2017a; Scansen, 2018).

The present study aims to evaluate the qualitative and morphometric characteristics of the coronary arteries of the dog by perfusion of the vascular beds with polyester resin, considering the morphometric differences of these structures in the different age groups of this animal species.

MATERIAL AND METHOD

Descriptive cross-sectional study in an accessible population of 30 hearts of dogs that died of natural causes in veterinary clinics in Bucaramanga, Colombia, of different ages, sizes and breeds. Dogs with a diagnosis of cardiac disease and/or cardiac trauma were excluded, as well as those who died by euthanasia because of the possibility of primary or secondary terminal cardiac disease. This study was approved by the ethics committee of the Universidad Industrial de Santander (Act 25 - 2024) and complies with the national Law 84 of 1989, corresponding to Chapter VI of the "National Statute for the Protection of Animals", on the use of animals in experimentation and research.

In consideration of the differences in weight and size of the dogs evaluated were categorized as follows: <10 kg (n=13), 10 - 19 kg (n=11), 20 - 29 kg (n=3), ≥30 kg (n=3) with an average age of 8.6 +/- 4.5 years. The hearts were explanted within their pericardial sac and with their main vessels, to preserve the coronary vasculature. The organ underwent a 6-hour exsanguination in a water source. After applying a repair stitch with silk in the most proximal segment of the right and left coronary arteries, a semisynthetic resin (Palatal GP40L 80 % and styrene 20 %) with red mineral color was injected. Specimens were fixed in a 10 % formaldehyde solution for 96 hours. Subepicardial fat adjacent to the coronary beds was released using 15 % KOH solution. Subsequently, the coronary arteries and their branches were dissected from their origin to their distal segments, and their trajectories, shapes, calibers, anastomoses, MBs and the presence of anatomical variations were recorded. The determination of the different types of coronary dominance was performed according to Schlesinger's criteria (Schlesinger, 1940). The distribution of left coronary dominance was performed according to DiDio and Wakefield's categorization (DiDio & Wakefield, 1975), with subtype I, when the RCA and LCA reach the cardiac crux and end as parallel SIB; subtype II, if the left ventricle and the entire interventricular septum are irrigated by the LCA, there is only one SIB originating from the CXB; and subtype III, if the SIB and the right posterior ventricular branches originate from the CXB, thus irrigating the left ventricle, the interventricular septum and the posterior wall of the right ventricle.

In those cases, in which MBs were observed, their length and location in the vessel were measured. The external diameter of these vessels was measured at 0.5 mm from their respective origins with a digital caliper (Mitutoyo®). To support the findings, a digital photographic record of the coronary vessels and their branches was taken with each specimen evaluated. The current Veterinary Anatomical Nomenclature Committee, Hanover, 2017 was used.

Statistical analysis. Descriptive statistics were performed using SPSS 20 software (SPSS, Chicago, IL, USA) and Microsoft Excel 2013. Continuous variables were expressed as mean and 95 % confidence interval. Descriptive statistics were calculated for each morphometric parameter and the Kolmogorov-Smirnov normality test was used for each sample. For quantitative variables, when comparing two independent groups, the Student's t-test was used. In the case of quantitative variables after normal distribution for groups, the ANOVA test was used. Data were expressed as mean and standard deviation for all measured sizes and lengths. The significance level for the statistical test was $p < 0.05$.

RESULTS

The heart weights of the thirty specimens for the <10 kg, 10 - 19 kg, 20 - 29 kg, ≥30 kg groups were 61.9 g, 101.0 g, 127.5 g, 175.0 g respectively. The heart weight to body weight ratio for dogs in each group was in turn 1.02 %, 0.73 %, 0.47 % and 0.52 % respectively.

Right coronary artery

The first segment of this artery was an average of three branches that irrigated the different segments of the anterior wall of the right ventricle, while two branches emerged from the second segment towards the atrial and ventricular territories. In 19 (63.3 %), hearts the right marginal branch (RMB) was found, which ended in the middle third (72.2 %) and in the upper third (27.8 %) (Table I). Statistically significant differences were found in the greater caliber of the RMB ended in the middle third of the acute margin in relation to those that ended in the upper third (p=0.036). In cases of short RMB, the acute margin was irrigated by anterior ventricular branches that deviated their course toward this territory.

Table I. Right coronary artery caliber and its branches.

Group (kg)	Right coronary artery (mm)							
	pRCA	mRCA	dRCA	RMB	RCB	DO-RCB	SANB	DO-SANB
<10	1.32	1.14	0.93	0.72	0.61	3.68	0.66	5.6
10-19	1.75	1.5	1.06	0.88	0.65	4.77	0.56	6.9
20-29	1.79	1.57	1.44	1.16	0.77	8.52	0.6	5.01
>30	3.12	2.22	1.40	1.28	1.35	6.33	0.97	7.54

pRCA: proximal caliber right coronary artery, mRCA: medial caliber right coronary artery. dRCA: distal caliber right coronary artery. RMB: right marginal branch. RCB: right cone branch. DO-RCB: distance to origin right cone branch. SANB: Sinoatrial node branch. DO-SANB: distance to origin sinoatrial node branch.

The right cone branch (RCB) originated from the RCA and ran between the base of the conus arteriosus and the middle portion of the right ventricle; it terminated in the conus arteriosus in 23 cases (76.6 %), in the upper third of the anterior ventricular wall of the right ventricle in 5 hearts (16.7 %) and in its middle third in two specimens (6.7 %). Among the different groups evaluated the caliber of the RCB ranged from 0.65 - 1.35 mm, while the distance from the emergence of the RCB to the origin of the RCA in the right aortic sinus was recorded in a range of 3.68 - 6.33 mm (Table I). The SANB was observed in 20 cases (66.7 %), ascending over the anterior wall of the right atrium until reaching the respective node; this structure presented in the >30 kg group a caliber of 0.97 mm (Table I). The RCA ended between the right margin and the crux cordis in 25 (83.3 %) hearts, from this segment the right posterior atrial branch and one or two posterior ventricular branches, while in 5 specimens (16.7 %) it ended at the acute margin of the right ventricle (Fig. 1).

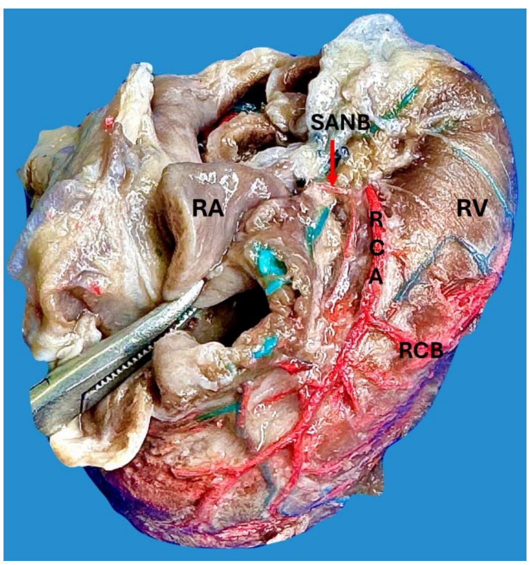

Fig.1. Anterosuperior view of the heart. (RA): Right atrium; (RV): Right ventricle; (RCA): Right coronary artery; (RCB): Right conus branch; (SANB): Sinoatrial node branch.

Left coronary artery

The LCA presented a significantly larger caliber than the RCA (p=0.01). The bifurcated expression in PIB and CXB was observed in 22 (73.3 %) hearts, and the trifurcation that gave rise to PIB, CXB and LDB was present in 8 (26.7 %) of the cases (Fig. 2). LDB terminated in the upper third in 6 hearts (75 %), in the lower third one specimen (12.5 %), and in the intermediate one case (12.5 %). The biometric findings of the LCA and its branches were recorded (Table II).

Table II. Morphometric characterization of left coronary artery and its larger branches.

Group (kg)	Left coronary artery (mm)															
	LCA-C	LCA-L	L-PIP	DA-PIB	PC-PIB	MC-PIB	DC-PIB	CXB-L	PC-CXB	MC-CXB	DC-CXB	LDB-C	PC-SIB	MC-SIB	DC-SIB	DA-SIB
<10	1.99	3.02	62.92	7.25	1.67	1.32	1.02	51.93	1.73	1.43	1.26	33.54	1.18	0.96	0.91	18.18
10-19	2.98	4.04	72.09	10.53	2.06	1.50	1.10	57.76	2.11	1.79	1.55	48.48	1.33	1.21	0.95	20.51
20-29	2.96	4.45	86.48	-	2.52	1.9	1.53	65.73	2.49	2.22	1.8	-	1.62	1.22	1.06	-
>30	4.00	3.94	101.51	-	2.94	2.33	1.33	65.67	3.05	2.48	1.63	46.37	2.51	1.83	-	36.43

LCA-C: left coronary artery caliber. LCA-L: left coronary artery length. DA-PIB: distance to the apex paraconal interventricular branch. PC-PIB: proximal caliber paraconal interventricular branch MC-PIB: medial caliber paraconal interventricular branch. DC-PIB: distal caliber paraconal interventricular branch. CXB-L: circumflex branch length. PC-CXB: proximal caliber circumflex branch. MC-CXB: medial caliber circumflex branch. DC-CXB: distal caliber circumflex branch. LDB-C: left diagonal branch caliber. PC-SIB: proximal caliber subsinusal interventricular branch. MC-SIB: medial caliber subsinusal interventricular branch. DC-SIB: distal caliber subsinusal interventricular. DA-SIB: distance to the apex subsinusal interventricular branch

The PIB in 20 (66.7 %) cases ended in the posterior aspect of the left ventricle, in 20 % in the apex and in the inferior third of the paraconal interventricular groove in four specimens (13.3 %). In the 10 - 19 kg group, the distance of ending to the apex was 10.53 + 4.46 mm (Table II). Three branches emerged from the PIB to the posterior wall of the left ventricle and four right ventricular branches (Figs. 2, 4 and 5).

The CXB coursed through the left ventricular atrioventricular groove and terminated in 28 specimens (93.3 %) in the subsinusal interventricular groove, while 2 (6.7 %) terminated in the posterior aspect of the right ventricle (Figs. 2 and 3). The length of this branch was 56.70 ± 6.75 mm, being statistically lower than the length of the PIB (p= 0.001) (Table II).

The left anterior ventricular branch (LAVB) emerged as the first branch of the PIB and presented its trajectory along the left ventricular wall: in 10 hearts (33.3 %), it ended in the middle third, 9 (30 %) in the lower third, 8 (26.7 %) in the apex and 3 (10 %) in the upper third. In the 10 -19 kg group it presented a length of 35.6 ± 12.9 mm and a proximal caliber of 1.16 ± 0.28 mm (Table III) (Figs. 2 and 4).

The left marginal branch (LMB) was found in 28 hearts (93.3 %). In 15 hearts (53.6 %) it ended in the distal ventricular third, 12 hearts (42.8 %) in the middle third and in one heart (3.6 %) in the apex. In the <10 kg group, it recorded a caliber of 0.98 ± 0.22 mm (Table III) (Figs. 2, 3 and 4).

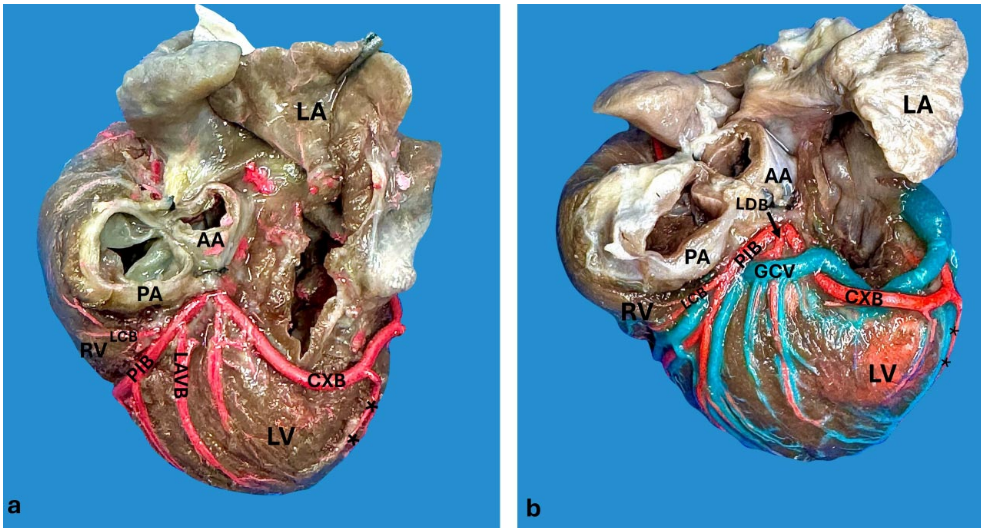

Fig. 2. Left surface of the heart. Division into two branches of the left coronary artery (a); division into three branches of the left coronary artery (b). (LA): Left atrium; (LV): Left ventricle; (RV): Right ventricle; (PA): Pulmonary artery; (AA): Aorta artery; (PIB): Paraconal interventricular branch; (CXB): Circumflex branch; (LDB): Left diagonal branch; (LCB): Left cone branch; (**): Left marginal branch; (LAVB): First left anterior ventricular branch; (GCV): Great cardiac vein.

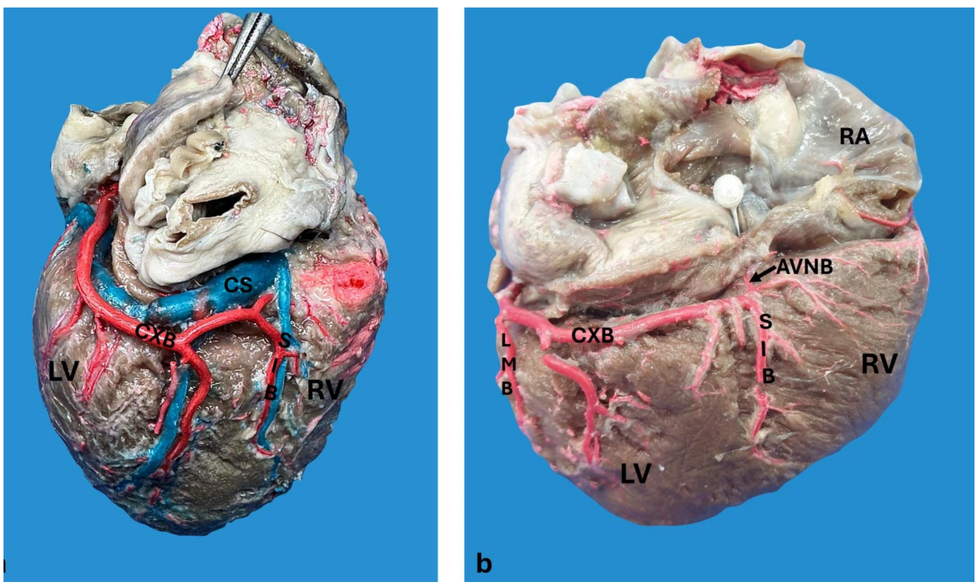

Fig. 3. Right surface of the heart. Left coronary dominance, subgroup II (a). Left coronary dominance, subgroup III (b). (LV): Left ventricle; (RA): Right atrium; (RV): Right ventricle; (CXB): Circumflex branch; (SIB): Subsinusal interventricular branch; (AVNB): Atrioventricular node branch; (LMB): Left marginal branch; (CS): Coronary sinus.

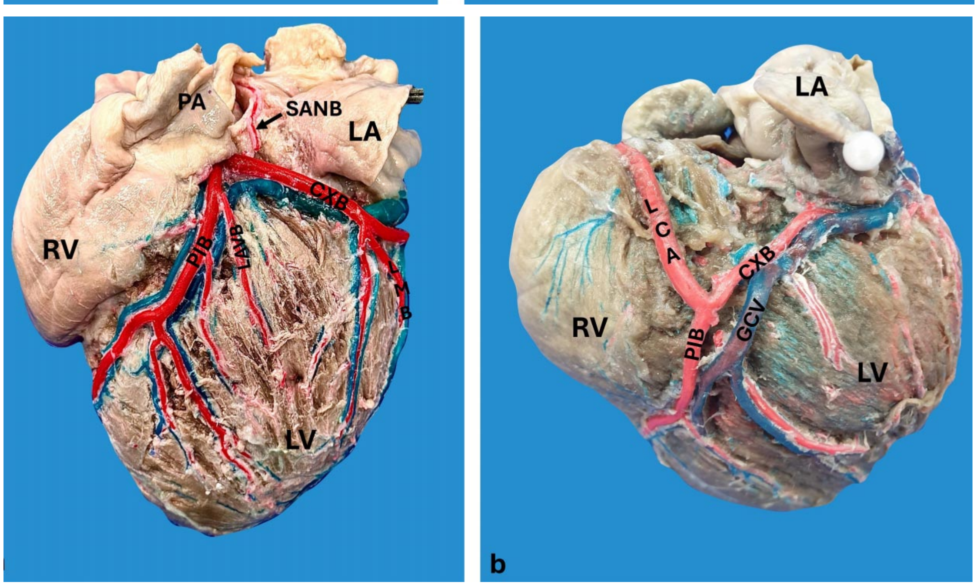

Fig. 4. Left surface of the heart. Division into two branches of the LCA (a). Heart with single coronary artery, which originates the right coronary artery and left coronary artery (b). (LA): Left atrium; (LV): Left ventricle; (RV): Right ventricle; (PA): Pulmonary artery; (LCA): Left coronary artery; (PIB): Paraconal interventricular branch; (CXB): Circumflex branch; (LMB): Left marginal branch; (LAVB): First left anterior ventricular branch; (SANB): Sinoatrial node branch; (GCV): Great cardiac vein.

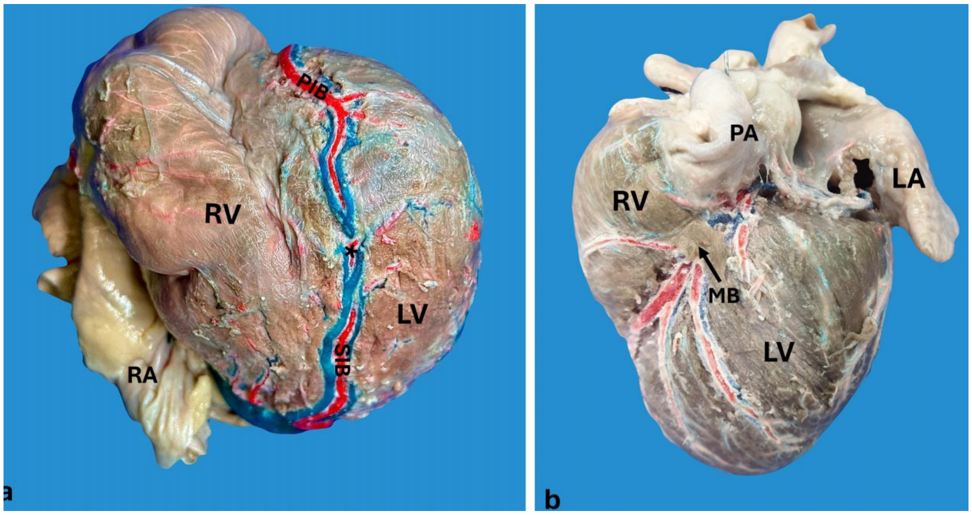

Fig. 5. Anastomosis between branches of the PIB and the SIB (a). Left surface of the heart (b). (LA): Left atrium; (RA): Right atrium; (LV): Left ventricle; (RV): Right ventricle; (SIB): Subsinusal interventricular branch; (PIB): Paraconal interventricular branch; (PA): Pulmonary artery; (*): Anastomosis on the apex of the heart; (GCV): Great cardiac vein; (MB): Myocardial bridge.

The SIB emerging from the CXB, in 16 hearts (53.3 %) terminated in the apex, in 8 hearts (26.7 %) in the lower third, in 5 hearts (16.7 %) in the middle third, while in one case (3.3 %) in the upper third of the homonymous sulcus (Fig. 3). The distance recorded from end of the SIB to the apex was 21.17 ± 7.31 mm (Table II).

The SANB was observed in 4 hearts (13.3 %) emerging from the CXB; in 6 specimens (20 %) it shared irrigation for the node with the branch derived from the RCA (Fig. 4). The left cone branch (LCB) was found in 28 specimens (93.3 %) (Fig. 2). It presented a caliber in the range of 0.66-0.86 mm (Table III). The atrioventricular node branch (AVNB) perfused adequately in 5 specimens (16.7 %), being a branch of the CXB and originating at the level of the cardiac crossover (Fig. 3).

Anastomosis at the level of the cardiac apex between the PIB and SIB was observed in 4 cases (13.3 %) (Fig. 5). The coronary dominance pattern observed in all the specimens evaluated in the present study was left. Subtype II was observed in 25 hearts (83.3 %) and subtype III in 5 cases (16.7 %) (Fig. 3).

MBs were observed in 2 cases (6.7 %), one in the <10 kg group defined as Type 1 (single bridge) located in the inferior segment of the left ventricular branch with a length of 8.9 mm; the other case was found in the 10 - 19 kg group, also Type 1, recorded in the superior segment of the PIB with a length of 6.6 mm (Fig. 5).

A case of relevant variation was observed characterized by the presence of a single right coronary ostium from which the RCA arises and from this the LCA as a branch that surrounds the conus arteriosus up to the paraconal interventricular groove, where it bifurcated giving rise to the PIB and CXB (Fig. 4).

Table III. Morphometric characterization of left coronary artery and its smaller branches.

	Left coronary artery (mm)											
Group (kg)	PC-LMB	DC-LMB	LMB-L	DA-LMB	PC-LAVB	DC-LAVB	LAVB-L	SANB-C	DO-RNS	AVNB-C	LCB-C	DO-RIC
<10	0.98	0.76	34.34	15.89	0.90	0.65	29.79	0.65	5.08	0.70	0.66	8.68
10-19	1.16	0.75	36.50	18.56	1.16	0.95	35.61	0.84	3.5	0.85	0.72	7.72
20-29	1.26	1.01	45.13	18.84	1.32	0.96	50.47	-	-	-	0.96	7.57
>30	1.26	1.08	32.731	25.62	1.34	0.94	64.25	0.81	-	-	0.86	8.62

PC-LMB: proximal caliber left marginal branch. DC-LMB: distal caliber left marginal branch. LMB-L: left marginal branch length. DA- LMB: distance to the apex left marginal branch. PC-LAVB: proximal caliber left anterior ventricular branch. DC-LAVB: distal caliber left anterior ventricular branch. LAVB-L: left anterior ventricular branch length. SANB-C: sinoatrial node branch caliber. AVNB-C: atrioventricular node branch caliber. DO-SANB: distance to origin sinoatrial node branch. LCB-C: left cone branch caliber. DO-LCB: distance to origin left cone branch.

DISCUSSION

Coronary irrigation in dogs, like other species, presents a usual pattern to which some degree of variability is added in terms of caliber, trajectories, divisions of the main trunks, dominance patterns and irrigated territories.

Understanding these differences enhances the anatomical concept and supports the cardiological activity in the veterinary clinic (Michell & Jefferson, 1962).

In this study, we described the coronary irrigation and its branches as well as its morphometry, while considering the body weight ranges of the dogs evaluated; which allowed to to determine the relative weight of the heart in relation to the weight of the individuals in each of the established groups. Our findings [<10 kg (1.03 %), 10 - 19 kg (0.72 %), 20 - 29 kg (0.37 %) and ≥30 kg (0.42 %)] similar to those described in previous reports, that the heart represents 0.6 - 1.1 % of the animal's body weight (Queiroz *et al*., 2018; Ragulya *et al*., 2024). While in humans, bovines and pigs similar heart weights have been expressed as a percentage of body weight of 0.51 %, 0.4 %, 0.4 %, respectively (Ocal & Cakir, 1993; Gaitskell *et al*., 2011; Gómez & Ballesteros, 2013). In agreement with Northup *et al*. this relative weight variation in dogs is influenced by factors such as breed, age, sex and size (Northup *et al*., 1957).

Relative dog heart weight appeared to have a proportionally inverse relationship to size, often resulting in a lower percentage of body weight attributed to cardiac mass in larger dogs (Queiroz *et al*., 2018). A similar correlation was observed in our study. Additionally, in previous studies have reported the inverse relationship to be associated with lower heart rates (Northup *et al*., 1957); although some studies argue that heart growth is more isometric, suggesting that the heart grows in proportion to body mass, challenging the notion of a strictly inverse relationship (Packard, 2021). In this regard, breeds known for their speed, such as greyhounds, have relatively higher heart weights (1.25 %), which may enhance their athletic performance (Schneider *et al*., 1964; Gunn, 1989).

The RCA in the sample originated from the ascending aorta in the right aortic sinus, following a slightly posterior descending trajectory and irrigating the atrioventricular groove. The caliber and length of the RCA vary significantly among canines in relation to their size and weight, and as in humans, sheep and other animal species the caliber of this vessel in the species evaluated is smaller than LCA (Ballesteros & Ramírez, 2008; Ballesteros *et al*., 2011; Gómez & Ballesteros, 2013). In the present study the proximal, middle and distal caliber presented a significant increase in proportion to weight in each group evaluated (Table I). Previous studies did not report this measurement considering body weight ranges. This information is relevant when considering the possibility of using endovascular devices in hemodynamic practice in dogs. The first segment of this artery presented an average of three branches, and the second segment two arterial branches in our study, being slightly lower than that reported by Oliveira *et al*. (2010) (6.5 branches). The ending of the RCA was observed mostly (83.3 %) between the right margin and the crux cordis, while in 16.7 % of cases in the acute margin, ending as RMB. These findings in previous studies have been reported in a qualitative form (Oliveira *et al*., 2010, 2011).

RMB was evident at 63.3 %, a finding considerably lower than that reported by Oliveira *et al*. (2010). The majority ending (72.2 %) of this vessel in the middle third of the acute margin of the heart is concordant with what has been reported in humans, pigs and bovines (Ballesteros & Ramírez, 2008; Gómez & Ballesteros, 2013; Gómez-Torres *et al*., 2023). The importance of this branch is highlighted, which in the face of increased heart rate and right ventricular pressure, can improve the total volumetric flow in the RCA, indicating its adaptability to the physiological demands of the myocardium (Oki & Awa, 1995), if we consider that dogs present smaller caliber and trajectory of the RCA compared to the LCA that results in the latter being in charge of the greater blood supply to the cardiac muscle.

The RCB emerged as the first branch of the RCA near its origin in the right aortic sinus. Its ending in the right anterior ventricular wall is concordant with that reported in human, pig and bovine studies (Olabu *et al*., 2007; Ballesteros & Ramírez, 2008; Cademartiri *et al*., 2008; Gómez & Ballesteros, 2013; Gómez-Torres *et al*., 2023), but this vessel in both dogs and bovines originates exclusively from the RCA (Gómez-Torres *et al*., 2023), while in pigs it has been reported with a frequency of 5.1 % (Gómez-Torres *et al*., 2023) and in humans in a range of 8 - 36 % (Olabu *et al*., 2007; Cademartiri *et al*., 2008; Ballesteros *et al*., 2011) originating directly from the right aortic sinus which has led to the latter scenario being referred to as the “third coronary”.

In our study, the frequency of the origin of the SANB from the RCA is like that reported in different human population (Olabu *et al*., 2007; Cademartiri *et al*., 2008; Ballesteros *et al*., 2011), whereas in pigs this branch originates in 100 % from the RCA and in bovines this vessel emerges mostly from the LCA (Gómez-Torres *et al*., 2023). The SANB presented a dual origin in 20 % of the cases in the present study, in contrast to Ovcina (2002) that reports only 10 % of node substitution by branches of the two coronary arteries. The importance of the irrigation of this structure has been emphasized because of the rich blood supply to the sinoatrial node as an antiarrhythmic and ischemic protective effect (Pina *et al*. 1975; Okmen & Okmen, 2009; Ballesteros *et al*. 2011; Gómez-Torres *et al*., 2023). This morphological feature allows us to understand the failure to provoke experimental ischemia of the sinoatrial node in the dog by ligating the RCA (Pina *et al*., 1975).

LCA in the species evaluated exhibited similar morphological characteristics compared to humans, pigs and bovines. In our study it bifurcated into the PIB and CXB in 73 % of cases, whereas in humans, pigs and bovines this same expression was reported in 52 %, 79 %, and 87.8 % respectively (Ballesteros & Ramírez, 2008; Gómez & Ballesteros, 2014; Gómez-Torres *et al*., 2023). The trifurcated configuration giving rise to PIB, CXB and LDB in our evaluated sample (26.7 %) was higher than reported in pigs and bovines, while for humans it has been reported in 22.1 - 42.2 % (Ballesteros & Ramírez, 2008; Gómez & Ballesteros, 2014; Gómez-Torres *et al*., 2023). In dogs, no tetrafurcated pattern of LCA was observed, a characteristic that in humans has been reported in a range of 5 % - 7 % (Reig & Petit, 2004; Ortale *et al*., 2005; Ballesteros & Ramírez, 2008).

The number of branches emerging from the PIB to irrigate the posterior walls of the right and left ventricles is slightly lower than that reported by Oliveria *et al*.; this characteristic has been recorded by other researchers only qualitatively (Blair, 1961; Longo Büll & Fernandes Boaro Martins, 2002; Oliveira *et al*., 2010, 2011). The RIP was found to end mostly in the posterior aspect of the left ventricle (66.7 %), in pigs this vascular structure in most cases ends in the apex (79 %) (Gómez & Ballesteros, 2014), while in humans it most frequently reaches the lower third of the posterior interventricular groove in 42-80 % (Sahni & Jit, 1990; Falci Júnior *et al*., 1993; Thiene *et al*., 2021); in bovines it ends at the apex (46.4 %) (Gómez-Torres *et al*., 2023).

In the present study we observed the termination of the CXB in the posterior aspect of the right ventricle in 6.7 % of the specimens and in the subsinusal interventricular groove or cardiac crux in 93.3 %, findings that are discordant with those reported by Oliveira *et al*. (2011) who described that this artery in dogs terminated beyond the crux cordis in 57.7 % of the cases, and directly in the subsinusal interventricular groove in 40 %. CXB finding in the subsinusal interventricular sulcus reported in bovines (82.1 %) is like our findings (Gómez-Torres *et al*., 2023). Whereas in humans, they report CXB finding in the posterior interventricular groove with a frequency of 7 - 23 %, this being the relevant feature of left coronary dominance (Baptista *et al*., 1991; Kalpana, 2003; Ballesteros & Ramírez, 2008). In pigs the CXB terminated mostly (64 %) in the posterior aspect of the left ventricle (Gómez & Ballesteros, 2014).

The LAVB with little data in previous literature, was observed in our study as the first branch of the PIB ending mostly (33.3 %) as in pigs in the middle third of the left margin of the heart (Gómez & Ballesteros, 2014), while in bovines and humans, the LAVB is longer and ends more frequently in the lower third of the left ventricle (Ballesteros & Ramírez, 2008; Gómez-Torres *et al*., 2023). This branch, due to its oblique and descending trajectory on the anterior wall of the left ventricle, allows us to deduce that it participates significantly in the irrigation of this cardiac surface.

The presence of LMB observed in our study (93.3 %) is concordant with that reported in previous dog and human studies (Baptista *et al*., 1991; Ballesteros & Ramírez, 2008; Oliveira *et al*., 2010). In pigs its presence is slightly lower (87.9 %) (Gómez & Ballesteros, 2014). Previous studies in dogs with findings congruent to ours, recorded that the termination of this branch was in the distal third of the left margin of the heart (53.3 %) (Oliveira *et al*., 2010, 2011) however, those studies recorded a high percentage of termination in the apex (46.7 %), unlike our results that in few cases this termination was observed (3.6 %). It is clarified that in both pigs and bovines, this branch ended in the middle third of the obtuse face of the heart in a range of 51 - 57.1 % (Gómez & Ballesteros, 2014; Gómez-Torres *et al*., 2023).

In the present study, we observed that the SIB emerged from the CXB and in most specimens (53.3 %) reached the apex of the heart; whereas Oliveira *et al*. (2010, 2011) recorded the termination of this vessel mainly in the lower third of the subsinusal interventricular. In bovines and pigs, the termination of the SIB is concordant with our findings (Gómez & Ballesteros, 2013; Gómez-Torres *et al*., 2023); whereas in humans, its ending has been reported in the lower third of the posterior aspect and in the apex in a range of 67.4 - 75 % (James, 1965; Margaris *et al*., 1997; Ballesteros *et al*., 2011). It was observed in our study that the coronary dominance pattern was left in the whole sample, in agreement with what is described in the literature (Álvarez Ramírez & Cruz Martínez, 2011; Oliveira *et al*., 2011). In bovines, a predominance of left coronary dominance was observed (Gómez-Torres *et al*., 2023). In humans and pigs, despite showing right coronary dominance, other types of dominance (left and balanced) can be observed (Ballesteros Acuña *et al*., 2007; Shni *et al*., 2008; Sahni *et al*., 2008; Gómez-Torres *et al*., 2017a; Gómez-Torres *et al*., 2017b).

The AVNB in all cases was observed as a branch of the CXB originating at the level of the cardiac crux; in bovines it originated from the RCA (25 %) and the CXB (75 %) (Gómez-Torres *et al*. 2023), whereas in pigs it emerges from the RCA in all specimens (Gómez & Ballesteros, 2013). In humans it originates mostly (89.6 %) in the left retroventricular branch (RCA branch) (Ballesteros *et al*., 2011).

The frequency of anastomoses observed in our study (13.3 %) at the level of the cardiac apex between the PIB and SIB, is slightly higher than in pigs (7.6 %) (Gómez & Ballesteros, 2013). In bovines, a presence of 57.1 % is described between the branches of the coronary arteries (Gómez-Torres *et al*., 2023). Noestelthaller *et al*. (2005) using the corrosion injection technique, reported in dogs the extensive intramyocardial anastomoses between the different branches of the coronary arteries, a scenario that allows improving left ventricular function in the face of advanced myocardial dysfunction, with the use of vasodilators in dogs with heart disease.

Tangkawattana *et al*. (1997) in their extensive study in dogs deceased by euthanasia report the presence of MBs in 30 % of the cases, while in our study this anatomical variant was observed in only 8.3 %. In bovines it has been reported in 21.4 % (Gómez-Torres *et al*., 2023), in pigs between 42.4 - 47.3 % (Kosin´ski & Koz?owski, 2010; Gómez & Ballesteros, 2015), and in humans in a range of 34 - 44.6 % (Sahni & Jit, 1991; Roberts *et al*., 2021). The clinical importance of this variation is evident as most coronary artery flow occurs in diastole and constriction of the coronary artery by a MB could affect perfusion of adjacent cardiac muscle (Scansen, 2017b). In addition, the adverse effect of MBs on coronary atherosclerosis has been reported, with a relationship being found between the presence of MBs and certain structural changes in the arterial wall (Zechmeister, 1971). Further studies may be warranted to understand whether this anatomical variation is associated with altered myocardial perfusion, such as the case of atherosclerosis that has been reported in canines (Hess *et al*., 2003; Jia *et al*., 2022; Zhao *et al*., 2022).

The rare case of common origin of the RCA and LCA in the right coronary ostium observed in our study has likewise been reported as a unique case in equines (Gómez-Torres *et al*., 2017b). The territories irrigated by the coronary arteries derived from that common trunk and their caliber are the usual for each of these branches, so it is inferred that this is a simple variant without clinical implications.

CONCLUSIONS

In the present study, a detailed description was made of the coronary irrigation and its branches, as well as its morphometry, considering the weight ranges of the dogs analyzed. This allowed us to determine the relationship between the relative weight of the heart and the body weight of the specimens, as well as to understand the precise differences of this vasculature in terms of calibers, lengths and trajectories in each of the groups evaluated.

The findings reported in the present study, in addition to enhancing the information on coronary irrigation in dogs, in the context of comparative anatomy, may contribute to the improvement of clinical and interventional management involved in the cardiology of the species.

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PINEDA-BETANCURT, I. A.; BALLESTEROS-ACUÑA, L. E. & GÓMEZ-TORRES, F. A. Caracterización cualitativa y morfométrica de las arterias coronarias en caninos (*Canis lupus familiaris*). Un estudio anatómico directo. *Int. J. Morphol., 43(3)*:1059-1069, 2025.

RESUMEN: La información en torno a la irrigación coronaria de los caninos es aún escasa a pesar de su gran importancia en el contexto de la anatomía comparada y de sus aplicaciones en la medicina veterinaria. El objetivo fue realizar una caracterización cualitativa y biométrica de las arterias coronarias en caninos. Mediante la técnica de perfusión de los lechos vasculares se inyectó resina semisintética (Palatal GP40L 80 % y estireno 20 %) en los lechos arteriales de 30 corazones de perros fallecidos en clínicas veterinarias, que de acuerdo con el peso se categorizaron así: <10 kg; (10 – 19 kg; 20 – 29 kg; ≥30 kg. La arteria coronaria izquierda presentó calibre de 3,25 mm, significativamente mayor al de la arteria coronaria derecha. (p=0,01). La arteria coronaria izquierda fue bifurcada en 22 (73,3 %) corazones, y la trifurcada en 8 (26,7 %). La rama interventricular paraconal finalizó en 20 casos (66,7 %) en la cara posterior del ventrículo izquierdo y en el grupo de 10 – 19 kg la distancia de finalización de esta rama al ápex fue 10,53 +/-4,46 mm. Se registró anastomosis a nivel del ápex cardiaco entre la rama interventricular paraconal y la rama interventricular subsinusal en 4 casos (13,3 %). En toda la muestra el patrón de dominancia coronaria fue izquierdo, observándose subtipo II en 25 corazones (83,3 %) y subtipo III en 5 casos (16,7 %). En 2 casos (6,7 %) se visualizaron puentes miocárdicos. La descripción detallada de las arterias coronarias y sus ramas, así como de su morfometría, considerando los rangos de peso de los caninos realizada en el presente estudio permite identificar las diferencias de esta vasculatura en cada uno de los grupos evaluados. Estos hallazgos podrán contribuir al mejoramiento de manejos clínicos e intervencionistas involucradas en la cardiología de la especie.

PALABRAS CLAVE: Caninos; Irrigación coronaria; Arteria coronaria izquierda, Arteria coronaria derecha; Dominancia coronaria.

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Corresponding author:
Luis E. Ballesteros-Acuña
Department of Basic Sciences
School of Medicine
Universidad Industrial de Santander
Cra 32 # 29-31
68002
Bucaramanga
COLOMBIA

E-mail: luisball@uis.edu.co