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ORIGINAL ARTICLE

Morphologic expression of the right coronary artery in horses. Comparative description with humans, pigs and other animal species

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ABSTRACT. The objective of this research was to characterise morphologically the right coronary artery and its branches in the horse. The right coronary arteries of 120 horse hearts were perfused with semi-synthetic resin (85% Palatal GP40L; 15% styrene) and mineral red dye. The morphological and biometric characteristics of the right coronary artery and its branches (digital calibrator) were assessed. The diameter of the right coronary artery was 6.72 ± 2.58 mm. The interventricular subsinusal branch ended at the apex in 94 specimens (78.4%). The right circumflex branch originated at the site of intersection of the subsinnusal interventricular sulcus and the atrioventricular septum, extended along the coronary sulcus with a convoluted trajectory, ended at the obtuse edge of the heart or even at the anterior aspect of the left ventricle in 62 hearts (52.5%), and at the middle segment of the left ventricle in 42 cases (35.6%), whereas in 14 samples (11.9%) it ended at the adjacent surface of the left ventricle. The right conus branch was found in 98 specimens (81.6%) and in 2 of them (1.7%) it emerged directly from the right aortic sinus (third coronary artery). The hearts exhibited right coronary dominance in 118 specimens (98.3%) and in 2 specimens (1.7%) the coronary dominance was balanced. No myocardial bridges were observed. The high incidence of right coronary dominance observed in this study is consistent with previous studies. Due to its similarity with the human heart, we may ratify the equine model for procedural and hemodynamic applications.

Key words: horse, coronary artery, dominance, heart.

RESUMEN. El objetivo de esta investigación fue caracterizar morfológicamente la arteria coronaria derecha del caballo y sus ramas. En 120 corazones de caballo se perfundieron las arterias coronarias derechas con resina semisintética (palatal GP40L al 85%; estireno al 15%) y color rojo mineral. Se evaluó las características morfológicas y biométricas de la arteria coronaria derecha y sus ramas (calibrador digital). El diámetro de la arteria coronaria derecha fue 6,72 +/–2,58 mm. La rama interventricular subsinusal finalizó en el ápex en 94 especímenes (78,4%). La rama circunfleja derecha se originó a nivel del sitio de cruce del surco interventricular subsinusal y el septum atrioventricular, se extendió a lo largo del surco coronario con una trayectoria contorneada y finalizando en el borde obtuso del corazón o incluso en la cara anterior del ventrículo izquierdo en 62 corazones (52,5%) y en el segmento medio del ventrículo izquierdo en 42 casos (35,6%), mientras que en 14 muestras (11,9%) esta finalizó en la superficie adyacente del ventrículo izquierdo. La rama derecha del cono, se encontró en 98 especímenes (81,6%) y en 2 corazones (1,7%) emergió directamente del seno aórtico derecho (tercera coronaria). Los corazones presentaron dominancia coronaria derecha en 118 muestras (98,3%) y en 2 casos (1,7%) la dominancia coronaria fue balanceada. No se observó puentes miocárdicos. La alta incidencia de dominancia coronaria derecha observada en este estudio es concordante con estudios previos. Debido a su semejanza con el corazón humano, nos permite ratificar el modelo equino para aplicaciones procedimentales y hemodinámicas.

Palabras clave: caballo, arteria coronaria, dominancia, corazón.

INTRODUCTION

The sparse reports that characterize the right coronary artery (RCA) in horses have been limited to a few morphological descriptions aimed at teaching animal anatomy and to a few computed tomography and magnetic resonance imaging studies. Previous works have failed to described trajectories, length, calibers or branches of the RCA in the horse (Rodriguez *et al* 1961, Rawlings 1977, Nickel *et al* 1981, Getty 1995).

The RCA originates in the anterior aortic sinus. It goes forward and somewhat downwards between the conus arteriosus and the right atrium, to the coronary sulcus, where it curves rightward and rearward. Then, it descends by the interventricular subsinusal sulcus (ISS) and ends near the cardiac apex (Nickel *et al* 1981, Getty 1995, Ozgel *et al* 2004). The right conus branch emerges from the proximal portion of the RCA, or directly from the aorta (third coronary artery), and descends from the upper segment of the anterior wall of the right ventricle (Rodriguez *et al* 1961).

The concept of right and left coronary dominance, widely used in humans, depends on which coronary artery gives origin to the interventricular subsinusal branch (ISB), or which one irrigates the greater part of the left posterior ventricular wall (Cavalcanti *et al* 1995, Ballesteros *et al* 2007). Right coronary dominance has been reported in horses, pigs, elephants and camels (Cave 1936, Sabathie and Pianetto 1941, Bertho and Gagnon 1964, Rawlings 1977, Ghazi and Tadjalli 1993, Sahni *et al* 2008, Yuan *et al* 2009) whereas left coronary dominance has been reported in donkeys, ruminants and dogs (Bertho and Gagnon 1964, Ozgel *et al* 2004). Right dominance is more prevalent in humans, reported in a wide range from 48% to 90% (Schlesinger 1940, James 1965, Cavalcanti *et al* 1995, Nerantzis *et al* 1996, Kalpana 2003, Ballesteros *et al* 2007).

The presence of myocardial bridges (MB), variable segments of the coronary arteries embedded in the

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ventricular myocardium, has not been assessed in horses (Rodriguez *et al* 1961, Rawlings 1977, Getty 1995); while in humans, pigs and camels have been reported within a range of 23-88% (Berg 1963, Ballesteros *et al* 2009, Kosiński *et al* 2010, Babiker and Taha 2013, Gómez and Ballesteros 2015[a]). MB have been considered in some works as a risk factor for the development of some cardiac conditions (Gow 2002, Rychter *et al* 2006).

The adequate knowledge of the coronary system of the horse enriches the concept of the morphology of the equine cardiovascular system, contributes to comparative anatomy, and facilitates its use for experimental physiological models and surgical procedures that use these structures. This work intends to generate meaningful information on the anatomy of the RCA in the horse through the assessment of fresh hearts and to compare the findings with those reported in humans and other animal species.

MATERIAL AND METHODS

This descriptive cross-sectional study evaluated the characteristics of the RCA in 120 hearts obtained from 2.5-3.5 years old horses weighing 250-300 kg, destined for the slaughterhouse in Bucaramanga, Colombia. The organs were subjected to an exsanguination process for 6 hours in a water source.

After applying a silk suture knot around the origin of the right coronary artery, it was injected with semi-synthetic resin, consisting of a mixture of Palatal GP40L 85% and styrene 15% with mineral red dye. The heart specimen was fixed in 10% formaldehyde solution for 96 hours, then the subepicardic fat adjacent to the coronary beds was removed by impregnating the anatomical pieces with 15% potassium hydroxide (KOH) for five minutes. Afterwards, the RCA and its collateral branches were dissected from their origin down to their distal segments. Using a digital gauge (Mitutoyo®), the external diameter of the vessels was measured at 0.5 cm of their respective origins. The trajectories and territories irrigated by the branches of the RCA were determined, as well as the ending site of these. The kind of coronary dominance was assessed in the samples evaluated, according to the criteria described by Schlesinger in humans, adapting them to the veterinary international terminology (Schlesinger 1940). For the right coronary dominance, the RCA irrigates the posterior aspect of the right ventricle, gives origin to the ISB and extends beyond the heart apex, through its right circumflex branch (RCXB), irrigating part of the posterior wall of the left ventricle. In the balanced coronary circulation, the RCA irrigates the right ventricle and the posterior aspect of the interventricular septum via the ISB, whereas the LCA irrigates the left ventricle, ending at the heart apex. For the left coronary dominance, the left circumflex branch (LCXB) irrigates the posterior aspect of the left ventricle, and ends as the ISB to irrigate the posterior segment of the interventricular septum and/or the posterior wall of the right ventricle. Similarly, the extension of the right coronary dominance was determined as mild when it reached the right third of the left ventricle, moderate when it reached its middle third, and prominent when it ended at the lateral third or the obtuse margin of the heart (Ballesteros *et al* 2007). The RCA and its branches were assessed for the presence of MB by determining the affected segment of the vessel, its length and the thickness of the myocardium above the bridge. A digital camera was used to take photographs of all of the evaluated pieces.

STATISTICAL ANALYSIS

The continuous variables (length and calibers) were analysed using t test, while the discrete variables (percentages) were assessed using Pearson's Chi^2 test. The results were evaluated using the "Epi - Info 3.5.4" statistical program. The significance level used was $P<0.05$.

RESULTS

The hearts of 73 male (60.8%) and 47 female (39.2%) horses weighing 1036 +/- 403.8 grams were evaluated. An average of 2.23 ± 0.94 ventricular branches emerged from the first segment of the RCA (from the origin to the right margin of the heart), and 2.26 ± 1.11 branches emerged from the second segment (from the right margin of the heart to near the intersection of the subsinusal interventricular sulcus and the atrioventricular septum).

The proximal, mid and distal diameters of the RCA were 6.72 ± 2.58 mm, 5.71 ± 1.75 mm, and 5.87 ± 1.92 mm, respectively. The ISB ended at the cardiac apex in 94 specimens (78.4%), while in one case (0.8%) it ended at the mid third of the sulcus of the same name (table 1 and figure 1). There were statistically significant differences between the numbers of ISB ending at the heart apex and those ending at the lower third of the SIS. (P=0.000).

The distance of ISB finalization with respect to the apex was 22.5 ± 7.08 mm. The diameters of this branch in their upper, mid and lower segments were 5.72 ± 1.9 mm; 4.49 ± 1.5 mm; and 2.57 ± 0.83 mm, respectively. The emergence of 3.2 ± 1.1 branches irrigating the right ventricle was noted, whereas 3.4 ± 1.2 branches irrigated the left ventricle. The RCXB originated at the level of the crux cordis, extended along the coronary sulcus with a convoluted trajectory, and had a slightly smaller diameter than the ISB. It ended at the obtuse edge of the heart or even at the anterior aspect of the left ventricle in 62 hearts (52.5%), at the mid segment of the left ventricle in 42 cases (35.6%), whereas in 14 samples (11.9%) it ended at the adjacent surface of the left ventricle. (figure 1).

A right conus branch (RCB) was found in 98 specimens (81.6%) with a diameter of 2.3 ± 0.8 mm. It ended at the level of the conus arteriosus in 13 samples (13.3%), at the upper third of the anterior wall of the right ventricle in 71 hearts (72.4%), and at the middle third in 14 specimens

Table 1. End of subsinusal interventricular branch (SIB) in homonym groove (SIG) and cardiac apex, by sex discrimination.

Right edge of the heart	Total sample	%	Males	%	Females	%
Middle third	1	0.8	1	1.4	0	0
Lower third	25	20.8	18	25	7	14.6
Ápex	94	78.4	53	73.6	41	85.4
Total	120	100	72	100	48	100

Table 2. End of right marginal branch (RMB) at the right edge of the heart, by sex discrimination.

Right edge of the heart	Total sample	%	Males	%	Females	%
Upper third	30	68.2	19	76	11	57.9
Middle third	13	29.5	6	24	7	36.8
Middle third	1	2.3			1	5.3
Total	44	100	25	100	19	100

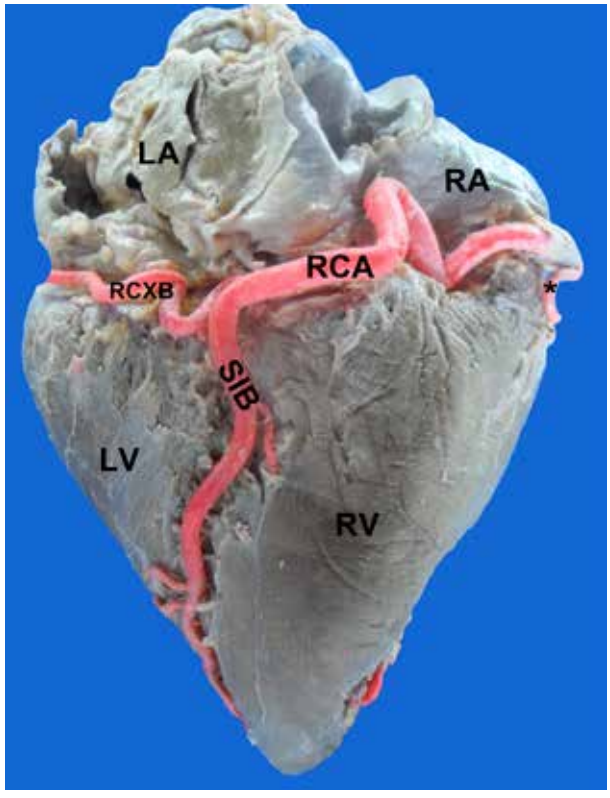

Figure 1. Posterior view of the heart. RA: right atrium. LA: left atrium. RV: right ventricle. LV: left ventricle. RCA: right coronary artery. SIB: subsinusal interventricular branch ending in the apex. RCXB: right circumflex branch. (*): right marginal branch.

(14.3%). In two hearts (1.7%) the RCB emerged directly from the right aortic sinus (third coronary artery).

The right marginal branch (RMB) was found in 44 samples (36.7%) with a diameter of 2.34 ± 0.7 mm. It ended at the upper third of the right margin of the heart in

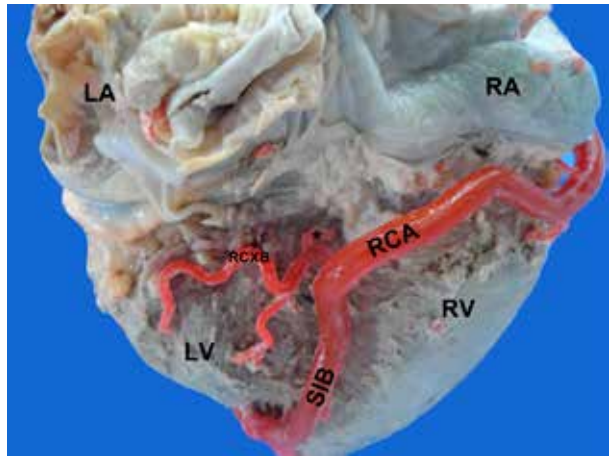

Figure 2. Right top view of the heart. RA: right atrium. LA: left atrium. RV: right ventricle. LV: left ventricle. RCA: right coronary artery. SIB: subsinusal interventricular branch. RCXB: right circumflex branch. (*): AV node branch.

30 cases (68.2%), without significant differences regarding sex (P=0.20) (table 2 and figure 1).

The atrioventricular node branch (AVNB) exhibited a caliber of 1.72 ± 0.61 mm; originated from the RCXB in 114 hearts (95%), whereas in 6 samples (5%) it was originated directly from the RCA. In the cases where it emerged from the RCXB, the distance from its origin to the bifurcation of the RCA was 8.2 ± 4.65 mm (figure 2).

Right coronary dominance was observed in 118 samples (98.3%), characterised by a very prominent RCXB that even irrigated territories of the anterior aspect of the left ventricle. Right dominance was prominent in 62 specimens (52.5%) (figure 3), moderate in 42 specimens (35.6%) (figure 4), and mild in 14 specimens (11.9%). In two cases (1.7%) the coronary dominance was balanced, with the left circumflex branch ending at the crux cordis. No MB were found in the specimens assessed.

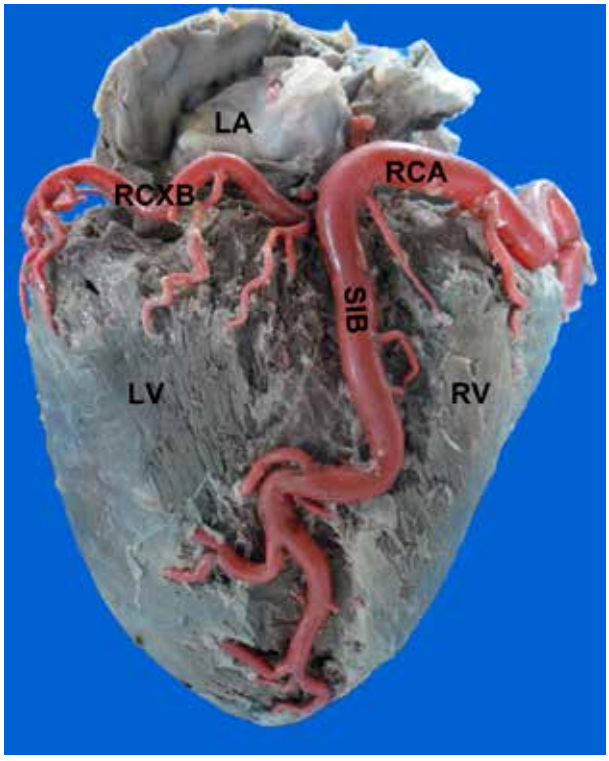

Figure 3. Posterior view of the heart. Prominent right coronary dominance. LA: left atrium. RV: right ventricle. LV: left ventricle. RCA: right coronary artery. SIB: subsinusal interventricular branch ending in the apex. RCXB: right circumflex branch.

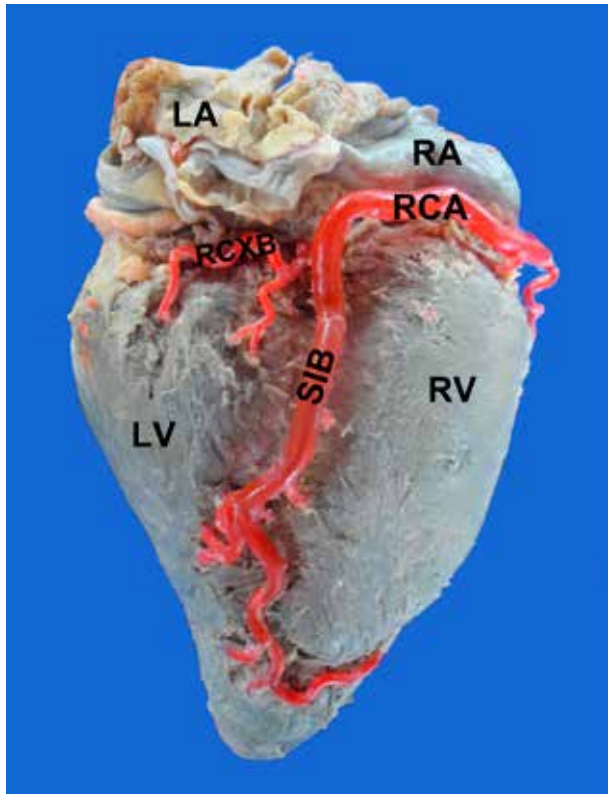

Figure 4. Posterior view of the heart. Moderate right coronary dominance. RA: right atrium. LA: left atrium. RV: right ventricle. LV: left ventricle. RCA: right coronary artery. SIB: subsinusal interventricular branch. RCXB: right circumflex branch.

DISCUSSION

The findings of the present work about the morphology of the RCA in the horse significantly enrich the information reported by previous studies on this subject, and they allow for analyses of these characteristics being made in other species like donkeys, pigs and even humans, within the context of comparative anatomy.

The caliber of the RCA in the horse reported by previous studies is greater than those found in the present study (6.72 mm) (Thtiroff *et al* 1984). Of note, a proximal diameter of the RCA of 0.8 mm and of the ISB of 0.7 mm have been reported in donkeys, figures being markedly smaller than those recorded in the present series. These differences could be explained by the methodology of measurement, and the sizes of the samples and the evaluated specimens.

Consistent with our findings, the ISB is described in donkeys, in elephants, camels and humans as ending mainly at the apex (Cave 1936, James 1965, Ghazi and Tadjalli 1993, Nerantzis *et al* 1994, Ozgel *et al* 2004, Yuan *et al* 2009, Ballesteros *et al* 2011). In horses (Bertho and Gagnon 1964) and pigs (Gómez and Ballesteros 2013), it is reported as ending at the middle third of the ISS. This morphologic expression was observed only in one sample in the present study. The posterior interventricular branch (equivalent to the ISB) has been reported as ending at the level of the lower third of the sulcus of the same name, or at the heart apex within a range of 60-70%, whereas short posterior interventricular branches are described as ending at the upper or middle thirds of such sulcus with an incidence of 30-42.5%. In these cases, irrigation compensation phenomena of the posteroinferior surface of the heart have been described, given by the distal segment of the anterior interventricular branch (equivalent of the paraconal interventricular branch), which, after surpassing the apex, distributes into the territory near the diaphragmatic face, by irrigating the segment not reached by the posterior interventricular branch (James 1965, Kalpana 2003, Ballesteros et al 2007). According to previous reports (Ghazi and Tadjalli 1993, Ozgel *et al* 2004, Yuan *et al* 2009), our series also reports the RCXB as extending along the coronary sulcus. Ozgel and Dursun 2005 reported the presence of five right and six left ventricular branches emerging from the ISB in donkeys, whereas the present work observed a lower number of branches (3.2 right and 3.4 left).

The RCB has been reported as ending at the level of the conus arteriosus in donkeys and camels (Ghazi and Tadjalli 1993, Ozgel *et al* 2004, Yuan *et al* 2009), which differs from our findings that show its ending at the upper

third of the anterior wall of the right ventricle (72.4%). Similarly, an anastomosis of the RCB with the left branch of the conus has not been described in donkeys, camels, elephants and pigs (Cave 1936, Ghazi and Tadjalli 1993, Ozgel *et al* 2004, Sahni *et al* 2008, Yuan *et al* 2009, Gómez and Ballesteros 2013). The presence of a third coronary artery is an unusual feature of the coronary circulation reported in some animal species like elephants and pigs (Cave 1936, Weaver *et al* 1986, Crick *et al* 1998, Sahni *et al* 2008, Gómez and Ballesteros 2013) with a small number of observations, which is consistent with our findings (1.7%). This feature is widely described in humans within a range of between 25-35% (Kalpana 2003, Ballesteros *et al* 2011).

According to Ozgel *et al* 2004 the RMB in donkeys ends in most cases at the upper third of the right margin of the heart, a feature that is consistent with our series. The presence of this branch has been reported in 60-93.7% in pigs (Sahni *et al* 2008, Gómez and Ballesteros 2013), as ending at the middle third of the right margin of the heart. The RMB in humans has been reported in 95.5% of the cases as ending at the lower third of the acute margin of the heart (Ballesteros *et al* 2011).

The AVNB has been described in camels and pigs, emerging from the RCXB within a range of 85-100%, an incidence consistent with the findings of the present series, and with reports for this morphologic expression in humans (Crick *et al* 1998, Pejkovic *et al* 2008, Sahni *et al* 2008, Saremi *et al* 2008, Ramanathan *et al* 2009, Ballesteros *et al* 2011, Gómez and Ballesteros 2013).

Previous studies have reported that the heart of the horse presents right coronary dominance (Sabathie and Pianetto 1941, Sahni *et al* 2008) just as ponies, elephants, and camels do (Cave 1936, Rawlings 1977, Ghazi and Tadjalli 1993, Yuan *et al* 2009). This is consistent with our findings, which found this variation in 96.7% of the cases. Previous studies on donkeys, ruminants, and dogs have reported left dominance in the analysed samples (Bertho and Gagnon 1964, Ozgel *et al* 2004). Right coronary dominance has been reported to occur in 66.5-100% of the cases in pigs (Weaver *et al* 1986, Crick *et al* 1998, Sahni *et al* 2008, Gómez and Ballesteros 2015[b]). In humans, right dominance has been described with low incidences (48-70%) (Ghazi and Tadjalli 1993, Cavalcanti *et al* 1995), medium incidences (70-84%) (Kalpana 2003, Ballesteros *et al* 2007) and high incidences (85-90%) (James 1965, Nerantzis *et al* 1996). Left coronary dominance in humans has been reported within a range of 5-20% (Schlesinger 1940, Kalpana 2003, Ballesteros *et al* 2007).

The presence of MB in the RCA and its branches has not been evaluated in previous studies. Vascular segments embedded in the myocardium have been described in the pig and the camel, affecting mainly the mid segment of the ISB with an incidence of 24-86% (Ghazi and Tadjalli 1993, Gómez and Ballesteros 2015[a]). Our study did not find any MB at the RCA and its branches. In humans, unlike other mentioned species, MB affects mainly the branches of the left coronary artery, such as the anterior interventricular branch and the diagonal branch, and with a very low incidence, branches of the RCA, have been reported. MB have been reported in humans within a wide range of 23-88% (Ballesteros *et al* 2009, Babiker and Taha 2013). In humans, MB have been hypothesised to constitute an anatomic substratum which together with other vascular factors, could cause cardiac arrhythmias, angina, and even sudden death (Gow 2002, Ballesteros *et al* 2009). Since horses do not exhibit any MB, this possibility could be ruled out in the context of the pathophysiology of the cardiovascular system.

In humans, understanding the diverse anatomical expressions of the RCA and its branches becomes imperative to address surgical and procedural issues in the clinical practice. Depurated skills supported by an appropriate knowledge of the morphology of these structures are required to perform several procedures such as catheterisation, stenting, bypassing, and perfusion of substances with physiological or pharmacological effects (Kang *et al* 2006, Krause *et al* 2009, Van Slochteren *et al* 2016). Therefore, due to the similarity of its coronary circulation, the heart of the horse is an excellent procedural model that allows for perfecting such techniques.

It is concluded that the right coronary dominance was found in most cases, with a RCXB extending to the anterior aspect of the left ventricle.

No MB were observed in the RCA and its branches, along with a very low incidence of a third coronary artery. The RCB was found to end primarily at the upper third of the anterior wall of the right ventricle, with the ISB primarily ending at the heart apex.

The morphology and biometry of the RCA and its branches found in this study were very similar to those found in the human heart, which allows to ratify the equine model for both procedural and hemodynamic applications.

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