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Morphometric Characterization and Anatomical Variations of Coronary Ostia in Human Hearts: Implications for Coronary and Aortic Interventions

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Research Article

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Abstract

Background

Coronary ostial morphology and position show considerable anatomical variation and are clinically relevant during coronary angiography, catheter-based interventions, aortic valve procedures, and aortic root surgery.

Objective

To evaluate the morphometric characteristics and anatomical position of the right and left coronary ostia and their clinical significance.

Methods

Sixty embalmed human heart specimens preserved in 10% formalin were examined. The number, shape, dimensions, and position of the coronary ostia were documented relative to the upper margin of the corresponding aortic cusps, sinotubular junction, and aortic valve commissures. Ostial and cusp dimensions were measured using a digital Vernier caliper.

Results

The mean diameter of the right coronary ostium was 4.78 mm (range, 2.7–8.8 mm), compared with 5.02 mm (range, 3.1–10.6 mm) for the left. Mean ostial height from the aortic root was 13.70 mm on the right and 14.17 mm on the left. Most right coronary ostia (86.7%) were located above the upper cusp margin, whereas 90% of left coronary ostia were at cusp level. Most ostia were below the sinotubular junction (right, 81.7%; left, 85%). Right coronary ostia were predominantly near Commissure I (58.3%), while left ostia were mainly central (56.7%) or near Commissure II (31.7%).

Conclusion

Coronary ostia demonstrate distinct side-specific variations in diameter, height, and spatial position. These morphometric findings provide useful anatomical reference data for coronary catheterization, aortic root surgery, coronary revascularization, and transcatheter aortic valve procedures.

INTRODUCTION

The coronary arteries arise from the coronary ostia located within the aortic sinuses and provide the principal arterial supply to the myocardium. The right coronary artery (RCA) usually originates from the

right aortic sinus (RAS) or anterior aortic sinus (AAS), whereas the left coronary artery (LCA) arises from the left posterior aortic sinus (LAS). The anatomical relationship of the coronary ostia to the aortic cusps, sinotubular junction (STJ), and commissures is variable and represents an important component of normal aortic-root anatomy [1–3].

Variations in the number, shape, diameter, height, and position of the coronary ostia may have important clinical implications. Abnormal ostial anatomy can complicate selective coronary catheterization and angiography and may influence coronary access during aortic valve surgery, aortic-root reconstruction, and transcatheter aortic valve implantation (TAVI). In particular, variations in ostial height and its relationship to the STJ and aortic valve apparatus are relevant to the risk of coronary obstruction during transcatheter and surgical valve procedures [1, 4, 5]. Although many coronary ostial variants are clinically silent, anomalous coronary origins and markedly abnormal ostial positions have also been associated with myocardial ischemia and, in selected circumstances, sudden cardiac death [6].

Previous anatomical and morphometric studies have demonstrated considerable variation in coronary ostial dimensions and topography among different populations. Cadaveric investigations have reported differences in ostial diameter, vertical position, relationship to the intercommissural line, and distance from the base of the aortic sinus, with the LCA ostium generally being larger than the RCA ostium [2, 3, 7]. More recent morphometric studies of the aortic root have further demonstrated that the three-dimensional relationships among the coronary ostia, aortic sinuses, valve cusps, and STJ are important for understanding the anatomical basis of contemporary aortic-valve interventions [5]. Nevertheless, population-specific cadaveric data describing the combined morphometric and topographic characteristics of the right and left coronary ostia remain limited, particularly when their relationships to the aortic cusps, STJ, and commissures are considered simultaneously.

Therefore, the present study was undertaken to provide detailed morphometric and topographic data on the coronary ostia in adult human hearts. The study specifically aimed to determine the number and morphology of the coronary ostia; measure their diameters and heights in relation to the aortic root; and document their positions relative to the upper margins of the aortic cusps, STJ, and aortic valve commissures. By establishing these anatomical reference measurements and identifying relevant positional variations, this study seeks to contribute to the anatomical basis for coronary angiography, catheter-based coronary procedures, aortic-root and valve surgery, and pre-procedural planning for transcatheter interventions [2–5].

MATERIALS AND METHODS

Study Design and Specimen Collection

This descriptive morphometric study was conducted on 60 embalmed adult human heart specimens preserved in 10% formalin. The specimens, including the heart and associated great vessels, had been previously dissected, fixed, and preserved at West Virginia University, USA, and subsequently transferred

to the Department of Human Structure and Neurobiology, College of Medicine and Health Sciences, National University of Science and Technology, Sohar, Oman. Each specimen was assigned a unique numerical identification code. Demographic information, including age, sex, and cause of death, was not available for the specimens and therefore was not included in the analysis. Hearts showing evidence of previous coronary artery bypass grafting, angioplasty, or other cardiac surgical procedures that could have altered the native morphology of the coronary ostia were excluded from the study.

Gross Anatomical Examination

Each heart was examined by standard gross anatomical dissection. The external surface was inspected to identify and trace the epicardial course of the right and left coronary arteries. Surrounding perivascular adipose tissue was carefully removed, as required, to expose the coronary arteries and their origins without disturbing the native configuration of the coronary ostia.

Preparation and Exposure of the Aortic Root

To obtain direct visualization of the coronary ostia, the ascending aorta was transected approximately 1 cm above the aortic valve commissures. A longitudinal incision was subsequently made through the posterior wall of the aorta between the right and left posterior (non-coronary) cusps. This method provided adequate exposure of the three aortic sinuses and their corresponding valve cusps, allowing direct inspection and measurement of the coronary ostia in relation to the aortic root and valve apparatus (Fig. 1).

Morphological Assessment of Coronary Ostia

The coronary ostia were systematically examined in each specimen. The following morphological characteristics were recorded:

1. Number of coronary ostia present within the aortic sinuses.
2. Shape of each ostium, classified as circular, oval, or other identifiable variant morphology.
3. Location of the ostium within the corresponding aortic sinus.
4. Presence or absence of accessory coronary arterial orifices.

The right and left coronary ostia were assessed independently to permit side-specific comparison of their anatomical characteristics.

Morphometric Measurements

All linear measurements were obtained directly from the exposed aortic root using a digital Vernier caliper. Measurements were recorded in millimetres (mm). For oval-shaped ostia, the maximum

longitudinal dimension (height) and transverse dimension (width) were measured. For circular ostia, the maximal diameter was recorded (Fig. 2).

The vertical position of each coronary ostium was determined in relation to two anatomical reference levels:

- the upper margin of the corresponding aortic valve cusp, and
- the sinotubular junction (STJ).

Based on these relationships, each ostium was categorized as being below, at, or above the respective reference level (Fig. 3).

Relationship of Coronary Ostia to Aortic Valve Commissures

The position of each coronary ostium within the aortic sinus was additionally assessed in relation to the aortic valve commissures. Ostia were categorized as either centrally located within the sinus or positioned close to Commissure I, II, or III. For this assessment, the caliper was positioned between the centre of the ostial opening and the nearest corresponding left and right commissural landmarks to determine the spatial relationship of the ostium to the commissures.

Measurement of Coronary Ostial and Aortic Cusp Height

The vertical height of the coronary ostium from the base of the corresponding aortic sinus was measured for both the right and left coronary ostia. One limb of the digital Vernier caliper was positioned at the centre of the ostial opening, while the other was placed at the base of the corresponding aortic sinus, providing a consistent reference for measurement (Fig. 4).

The height of the corresponding aortic cusp was measured using the same anatomical reference technique. Thus, ostial height and cusp height were obtained using comparable reference points, allowing their relative vertical positions to be characterized (Fig. 4).

Specimens in which the ostium was markedly displaced toward a commissure were excluded from ostial-height measurements because such displacement could compromise the accuracy and reproducibility of the vertical measurement.

Data Recording and Analysis

All morphological observations and morphometric measurements were systematically recorded for each specimen using the assigned specimen identification code. Continuous variables were expressed in millimetres and summarized using descriptive statistics, including mean and range. Categorical

anatomical characteristics, including ostial position and relationship to the aortic cusps, sinotubular junction, and commissures, were expressed as frequencies and percentages. Right- and left-sided coronary ostial characteristics were subsequently compared descriptively to identify anatomical patterns and variations.

The analysis was primarily descriptive because the study was designed to characterize the anatomical morphology and morphometry of coronary ostia in a cadaveric sample. The resulting measurements were used to establish reference values and document positional variations of the coronary ostia within the aortic root.

RESULTS

Morphometric characteristics of the coronary ostia

Morphometric measurements of the right and left coronary ostia demonstrated differences in ostial diameter and vertical position within the corresponding aortic sinuses. The mean diameter of the right coronary ostium was 4.78 mm (range, 2.7–8.8 mm), whereas that of the left coronary ostium was 5.02 mm (range, 3.1–10.6 mm). Thus, the left coronary ostium showed a slightly greater mean diameter than the right coronary ostium (Table 1).

Table 1
Morphometric measurements of the coronary ostia and corresponding aortic cusps

Parameter	Right coronary ostium (mm)	Left coronary ostium (mm)
Diameter of ostium	4.78 (2.7–8.8)	5.02 (3.1–10.6)
Height of aortic cusp	10.95 (7.2–14.4)	11.25 (9.0–15.9)
Height of ostium from aortic root	13.70 (8.6–21.8)	14.17 (7.7–17.5)

*Values are presented as mean (range).

The mean height of the right aortic cusp was 10.95 mm (range, 7.2–14.4 mm), compared with 11.25 mm (range, 9.0–15.9 mm) for the left aortic cusp. The corresponding mean height of the coronary ostium measured from the base of the aortic root was 13.70 mm (range, 8.6–21.8 mm) on the right and 14.17 mm (range, 7.7–17.5 mm) on the left. In both coronary territories, the mean ostial height was greater than the corresponding mean cusp height.

Position of coronary ostia in relation to the aortic cusps

Considerable side-to-side variation was observed in the vertical position of the coronary ostia relative to the upper margin of the corresponding aortic cusps. The right coronary ostium was located above the upper cusp margin in 52 specimens (86.7%), at the cusp level in 7 specimens (11.7%), and below the cusp margin in 1 specimen (1.6%) (Table 2).

Table 2
Distribution of coronary ostia according to their relationship with the aortic cusps, sinotubular junction, and commissures.

Parameter	Level	Right coronary ostium, n (%)	Left coronary ostium, n (%)
Position relative to upper margin of cusp	Below	1 (1.6)	0 (0)
	At	7 (11.7)	54 (90.0)
	Above	52 (86.7)	6 (10.0)
Position relative to sinotubular junction	Below	49 (81.7)	51 (85.0)
	At	4 (6.7)	3 (5.0)
	Above	7 (11.6)	6 (10.0)
Position relative to commissures	Central	21 (35.0)	34 (56.7)
	Near Commissure I	35 (58.3)	0 (0)
	Near Commissure II	0 (0)	19 (31.7)
	Near Commissure III	4 (6.7)	7 (11.6)

In contrast, the left coronary ostium was located predominantly at the level of the upper cusp margin, accounting for 54 specimens (90.0%). Six left coronary ostia (10.0%) were positioned above the cusp margin, whereas none were located below it. Therefore, the distribution of ostial position relative to the cusp margin differed substantially between the right and left coronary ostia.

Position of coronary ostia relative to the sinotubular junction

Most coronary ostia were located below the sinotubular junction (STJ) on both sides. The right coronary ostium was below the STJ in 49 specimens (81.7%), at the STJ level in 4 specimens (6.7%), and above the STJ in 7 specimens (11.6%).

Similarly, 51 left coronary ostia (85.0%) were located below the STJ, while 3 (5.0%) were at the level of the STJ and 6 (10.0%) were positioned above it. Thus, the majority of both right and left coronary ostia were situated below the STJ, with relatively few specimens demonstrating an ostium at or above the junction.

Relationship of coronary ostia to the aortic commissures

The relationship of the coronary ostia to the aortic valve commissures also demonstrated distinct right–left patterns. On the right side, 35 ostia (58.3%) were located near Commissure I, 21 (35.0%) occupied a

central position within the sinus, and 4 (6.7%) were located near Commissure III. No right coronary ostium was identified near Commissure II.

On the left side, 34 ostia (56.7%) were centrally positioned within the sinus, 19 (31.7%) were located near Commissure II, and 7 (11.6%) were located near Commissure III. No left coronary ostium was identified near Commissure I.

Overall, the morphometric findings demonstrated a slightly greater mean ostial diameter on the left than on the right, with distinct differences in the vertical and commissural distribution of the two coronary ostia. The right coronary ostium was most frequently positioned above the upper cusp margin and near Commissure I, whereas the left coronary ostium was predominantly at the cusp level and centrally positioned within the corresponding aortic sinus.

DISCUSSION

The present study provides a detailed morphometric and topographic assessment of the coronary ostia in 60 embalmed human hearts, with particular emphasis on ostial diameter, ostial height, position in relation to the aortic cusps and sinotubular junction (STJ), and spatial relationship with the aortic commissures. The findings demonstrate substantial anatomical variability despite the generally consistent origin of the right coronary artery (RCA) from the right/anterior aortic sinus and the left coronary artery (LCA) from the left/posterior aortic sinus. Such variability is clinically important because the coronary ostia represent the interface between the aortic root and the coronary circulation and are directly encountered during coronary angiography, selective catheterization, aortic root surgery, coronary reimplantation, transcatheter aortic valve implantation (TAVI), and delivery of cardioplegic solutions [8–12].

Principal morphometric findings and comparison with previous studies

In the present study, the mean diameter of the RCA ostium was 4.78 mm (range 2.7–8.8 mm), whereas that of the LCA was 5.02 mm (range 3.1–10.6 mm). Thus, the LCA ostium was approximately 0.24 mm larger on average than the RCA ostium. Although the difference in mean diameter was relatively small, the wider range observed on the left indicates considerable individual variation. A larger LCA ostial diameter has also been reported in previous cadaveric and radiological studies, supporting the observation that the LCA ostium is generally wider than the RCA ostium [10, 1, 2, 13]. Cavalcanti et al., in a morphometric study of 51 human hearts, reported mean ostial diameters of 4.75 ± 0.93 mm for the LCA and 3.46 ± 0.94 mm for the RCA, demonstrating a substantially greater side-to-side difference than that observed in the present study [2]. Similarly, a combined cadaveric and angiographic investigation reported significantly smaller RCA ostial diameters than LCA ostial diameters [13]. These differences may reflect population characteristics, specimen selection, methodological differences, and the reference level used for measuring the ostium.

The larger diameter of the LCA ostium may be considered anatomically appropriate because the left coronary circulation supplies a large proportion of the ventricular myocardium through the anterior interventricular and circumflex systems. However, ostial diameter should not be interpreted solely in terms of myocardial territory. The dimensions of the ostium are also influenced by the three-dimensional geometry of the aortic sinus, coronary take-off angle, arterial wall architecture, age-related remodelling, and methodological differences between cadaveric and imaging studies [1, 11]. Therefore, the relatively small difference between the mean RCA and LCA diameters in the present study should not be regarded as evidence that the two ostia are functionally equivalent in every individual.

As shown in Table 3, the findings of the present study are broadly comparable with those reported in previous morphometric investigations, although variations in sample characteristics and measurement techniques should be considered. Cavalcanti et al. [2], who examined 51 hearts, reported mean coronary ostial diameters of 3.46 ± 0.94 mm for the right coronary artery (RCA) and 4.75 ± 0.93 mm for the left coronary artery (LCA), demonstrating a significantly wider LCA ostium than the RCA ostium. Similarly, Al-Hussainy et al. [13], based on 60 hearts and 400 angiographic examinations, reported mean diameters of 3.4 mm for the RCA and 4.4 mm for the LCA, again showing a narrower RCA ostium compared with the LCA. In the present study of 60 cadaveric hearts, the mean ostial diameters were 4.78 mm for the RCA and 5.02 mm for the LCA, indicating that the LCA ostium was slightly wider than the RCA ostium. Thus, the present findings are consistent with the general pattern reported by Cavalcanti et al. [2] and Al-Hussainy et al. [13], in which the LCA ostium tends to have a greater diameter than the RCA ostium, although the absolute measurements differ between studies. Joshi et al. [1], who studied 105 Indian cadaveric hearts, documented considerable population-specific variation in coronary ostial morphology. They reported that most coronary ostia were located at or above the upper margin of the corresponding aortic cusps and below the sinotubular ridge, with the LCA ostia predominantly occupying a central position, whereas the RCA ostia showed greater positional variability. Collectively, these observations indicate that coronary ostial dimensions and positions exhibit measurable inter-population and individual variation, which may have important implications for coronary angiography, catheter-based procedures, and surgical interventions involving the aortic root and coronary arteries.

Table 3
Comparison of coronary ostial diameter with previous morphometric studies.

Study	Sample	RCA ostium (mean)	LCA ostium (mean)	Principal observation
Cavalcanti et al. [2]	51 hearts	3.46 ± 0.94 mm	4.75 ± 0.93 mm	LCA significantly wider than RCA
Al-Hussainy et al. [13]	60 hearts + 400 angiograms	3.4 mm	4.4 mm	RCA narrower than LCA
Joshi et al. [1]	105 Indian hearts	Morphometric variation documented	Morphometric variation documented	Population-specific ostial variation
Present study	60 hearts	4.78 mm	5.02 mm	LCA slightly wider than RCA

The present findings are broadly concordant with this general anatomical pattern, although the magnitude of right-sided displacement was more pronounced in the current series. Such differences reinforce the importance of considering population-specific anatomical variation rather than if a single set of measurements represents all human populations. The comparison demonstrates that the absolute values vary between studies, but the recurring finding is that the LCA ostium is generally larger than the RCA ostium [1, 2, 13]. Differences between studies may result from population, sample composition, preservation, measurement technique, definition of the ostial margin, and whether measurements were obtained from cadaveric or angiographic material.

Relationship of the coronary ostia to the aortic cusps

A notable finding of the present study was the marked asymmetry between the RCA and LCA ostial positions relative to the upper margin of the corresponding aortic cusps. Approximately 86.7% of RCA ostia were located above the upper margin of the cusp, 11.7% were at cusp level, and 1.6% were below it. In contrast, 90% of LCA ostia were located at the level of the cusp and only 10% were above it. No LCA ostium was found below the upper cusp margin. These observations indicate that the vertical position of the RCA ostium is more variable in relation to the valve cusp than that of the LCA ostium in the present sample.

This right–left asymmetry is clinically relevant because the height and orientation of the coronary ostia determine the approach required for selective coronary cannulation. An ostium positioned unusually high or unusually low may not align readily with the expected catheter trajectory, particularly when standard catheter shapes are used. Anatomical studies have similarly demonstrated considerable variation in the vertical and circumferential position of the coronary ostia [1, 2, 13, 14]. Joshi et al. reported that approximately 84% of coronary ostia in their Indian cadaveric series were located at or above the level of the upper cusp margin, whereas the majority were below the sinutubular ridge [1]. The present study therefore supports the general concept that the coronary ostia preferentially occupy the upper part of the aortic sinuses but remain predominantly below the STJ.

The apparent discrepancy between the present study and some previous studies should not necessarily be considered contradictory because the reference landmarks differ. An ostium may be above the upper margin of the cusp but remain well below the STJ. Consequently, the vertical position relative to the cusp and the position relative to the STJ should be regarded as complementary rather than interchangeable measurements [1, 2, 13, 14].

Relationship to the sinotubular junction

As summarized in Table 4, the present findings demonstrate a clear predominance of coronary ostial origin below the sinotubular junction (STJ). In the present series, 81.7% of right coronary artery (RCA) ostia and 85.0% of left coronary artery (LCA) ostia were located below the STJ, whereas only 6.7% of RCA and 5.0% of LCA ostia were situated at the level of the STJ. Ostia located above the STJ accounted for 11.6% of RCA and 10.0% of LCA cases. Thus, approximately four-fifths of both coronary ostia originated within the aortic sinuses below the STJ, indicating that a sub-STJ position represents the predominant anatomical configuration. This observation is broadly consistent with the findings of Joshi et al. [1] and Al-Hussainy et al. [13], who reported that coronary ostia were predominantly located below the sinotubular ridge/STJ. In contrast, Cavalcanti et al. [2] described a more variable distribution of ostial positions in relation to the corresponding aortic reference level. The overall agreement among studies supports the predominance of a sub-STJ coronary origin, while the proportion of ostia occurring at or above the STJ may reflect interindividual anatomical variation. These variations are clinically relevant because the vertical position of the coronary ostia in relation to the STJ can influence coronary perfusion, interpretation of aortic root anatomy, and procedural planning during coronary angiography, aortic root interventions, and transcatheter or surgical aortic valve procedures.

Table 4
Comparison of coronary ostial position relative to the sinotubular junction (STJ) among published studies and the present series.

Study	RCA below STJ	LCA below STJ	General interpretation
Joshi et al. [1]	Predominantly below	Predominantly below	Majority below sinutubular ridge
Cavalcanti et al. [2]	Variable	Variable	Ostia distributed around intercommissural reference level
Al-Hussainy et al. [13]	Predominantly below	Predominantly below	Below-STJ location most common
Present study	81.7%	85.0%	Sub-STJ origin predominates

This finding is consistent with previous anatomical and angiographic observations that coronary ostia normally arise below the STJ, although the exact vertical distance varies among individuals and populations [1, 2, 13, 14]. Cavalcanti et al. observed that the coronary ostia could occur above, below, or at the level of the intercommissural line, while Joshi et al. reported that 89% of ostia were below the sinutubular ridge [1, 2]. A more recent cadaveric and angiographic study likewise reported that most

coronary ostia were below the STJ [13]. The consistency of this general pattern across studies supports the concept that the sinus region immediately below the STJ represents the usual developmental and anatomical territory for coronary arterial attachment.

The clinical significance of this relationship is considerable. During coronary angiography, the catheter must enter the ostium without excessive pressure against the aortic wall or valve apparatus. An ostium that is unusually high, particularly one approaching or extending above the STJ, may be difficult to engage selectively and may result in nonselective contrast injection or prolonged catheter manipulation. Conversely, a low-lying ostium may be exposed to different mechanical relationships with the aortic valve and may become particularly important during transcatheter or surgical aortic valve procedures [4, 11, 12].

It is important, however, to distinguish an ostium located above the STJ from a formally defined "high take-off" coronary artery. The present study classified ostia as above, at, or below the STJ but did not provide a continuous measurement of the distance above the STJ. Therefore, the 11.6% right-sided and 10% left-sided ostia located above the STJ should be interpreted as "suprasinotubular" or "above-STJ" positions rather than automatically classified as high-take-off anomalies according to a specific millimetric definition. This distinction would improve methodological precision in a revised manuscript.

Commissural relationship and three-dimensional ostial anatomy

The present study provides an additional clinically useful observation by describing the relationship of the ostia to the aortic commissures. On the right, 58.3% of ostia were situated near Commissures I, while 35% were central and 6.7% were near Commissure III. No right coronary ostium was identified near Commissure II. In contrast, the left coronary ostium was centrally located in 56.7% of specimens, followed by positions near Commissure II in 31.7% and Commissure III in 11.6%; no left ostium was located near Commissure I.

These findings demonstrate that the coronary ostia cannot be adequately characterized by vertical height alone. Their circumferential position within the sinus is also important because the aortic root is a three-dimensional structure in which the relationship between ostium, cusp, commissure and STJ changes simultaneously. Earlier morphometric investigations similarly emphasized the importance of the relationship of the coronary ostia to the commissures and aortic cusps [1, 2, 14]. The predominance of a central position for the LCA ostium in the present series is particularly consistent with observations from Indian cadaveric material in which the left coronary ostium was frequently centrally placed [1].

From an interventional perspective, circumferential displacement may affect the angle of catheter approach and the stability of catheter engagement. It is also important during aortic valve surgery because coronary reimplantation, valve-sparing root procedures, and prosthetic valve implantation require precise recognition of the relationship between the coronary buttons and the aortic

commissures. Failure to recognize an unusual circumferential position may result in malposition, distortion, kinking, or compromised coronary flow following surgical reconstruction [15].

Embryological basis of coronary ostial position and variation

The anatomical variability identified in the present study can be interpreted in the context of coronary vascular development. Coronary artery formation is a complex embryological process involving the proepicardial organ, epicardium-derived cells, vascular progenitors, and formation and remodelling of a subepicardial vascular plexus. The coronary arterial system does not simply arise as direct outgrowths from the aorta; rather, a developing vascular plexus establishes a connection with the aortic root and subsequently remodels into the mature coronary arteries [16–19].

During human development, the proepicardial organ contributes to the formation of the epicardium, and subepicardial vascular networks subsequently develop around the myocardial surface. Human embryological studies have demonstrated that the developing vascular plexus eventually penetrates the base of the aorta to establish the coronary ostia [17]. The proximal connection of the developing coronary arteries to the aorta occurs relatively late in cardiac development, after formation of the epicardial vascular plexus [20]. Thus, the final position of the coronary ostia reflects a coordinated interaction between the developing coronary plexus and the morphogenesis of the aortic root.

This developmental mechanism provides a plausible basis for the anatomical variability observed in adult hearts. As the coronary vascular plexus approaches and establishes connections with the aortic root, slight differences in the site of vascular attachment, remodelling, and subsequent growth may result in differences in ostial height, circumferential location, diameter, and relationship to the commissures. Contemporary embryological models suggest that the coronary vascular plexus grows toward the aortic root under the influence of molecular signals including vascular endothelial growth factor-related pathways, CXCL12/CXCR4 signalling, fibroblast growth factor pathways, and other regulators of vascular patterning [16, 18, 19].

Importantly, the developmental process also explains why congenital coronary anomalies can involve both the number and location of coronary ostia. Failure of normal plexus remodelling or abnormal aortic attachment may result in accessory ostia, ectopic origins, anomalous coronary courses, or abnormal take-off positions [16, 21]. The relatively unusual positions observed in the present study may therefore represent the normal anatomical spectrum generated by variation during coronary vascular remodelling rather than necessarily indicating pathological disease.

The embryological basis is particularly relevant to the observed difference between the right and left coronary ostia. The coronary arteries develop in association with the aortic root rather than through a completely symmetrical developmental process. The distinct geometry of the right and left aortic sinuses, together with asymmetric remodelling of the coronary vascular plexus, may contribute to the different patterns of ostial height and circumferential position identified in the current study [16, 20, 21].

This provides a developmental framework for understanding why the RCA in the present series showed a strong tendency toward a higher position relative to the cusp margin, whereas the LCA was more frequently located at cusp level.

Clinical significance in coronary angiography and catheter-based intervention

The clinical importance of coronary ostial morphometry is particularly evident during diagnostic coronary angiography and percutaneous coronary intervention. Successful selective cannulation requires alignment of the catheter tip with the coronary ostium, and abnormal ostial height, circumferential displacement, unusual diameter, or anomalous origin may make engagement difficult [1, 9, 11, 14]. Knowledge of the expected anatomical range can therefore help the operator recognize an anatomical variant rather than interpreting failure of selective engagement as evidence of coronary occlusion or absence.

The wider range of ostial diameters observed in the present study also has practical implications. A very small ostium may make catheter engagement more difficult and may increase the possibility of ostial trauma when excessive manipulation or deep intubation occurs. Conversely, an unusually large ostium may require careful differentiation from an accessory coronary origin or other anatomical variant [11, 13]. The current measurements therefore provide useful anatomical reference values, although clinical application should always incorporate patient-specific imaging rather than relying exclusively on cadaveric averages.

Anomalous coronary origins are particularly important because some patterns can be associated with myocardial ischemia, arrhythmia, or sudden cardiac death. The clinical importance of anomalous coronary anatomy has been recognized in both angiographic and anatomical studies, particularly when an anomalous artery follows a potentially hazardous course between major great vessels [1, 21]. However, the present study evaluated ostial morphology and location rather than the complete three-dimensional course of the coronary arteries; therefore, it cannot determine the clinical risk associated with any individual ostial variant.

Implications for TAVI and aortic valve interventions

The findings are also directly relevant to transcatheter aortic valve implantation. During TAVI, the prosthetic valve frame and displaced native valve tissue may compromise the coronary ostia, particularly when the coronary arteries arise at a relatively low height or when the aortic sinus is small. Clinical registry data have demonstrated that coronary obstruction after TAVI, although uncommon, can be catastrophic, and lower coronary height and smaller sinus dimensions are important anatomical risk factors [4].

The present study found that most ostia were below the STJ, with mean ostial heights from the aortic root of 13.70 mm on the right and 14.17 mm on the left. These values provide useful anatomical

reference information, but they should not be interpreted as direct TAVI risk thresholds because the present measurements were obtained from fixed cadaveric hearts and did not include annular height, sinus of Valsalva diameter, leaflet length, valve-to-coronary distance, or prosthesis-specific parameters. Contemporary imaging guidance emphasizes that coronary obstruction risk is determined by a combination of coronary height, sinus dimensions, annular anatomy, leaflet characteristics, and prosthesis configuration rather than coronary height alone [4, 22].

The approximately 10% of coronary ostia located above the STJ in the present sample are also relevant to surgical and transcatheter planning. A coronary ostium that lies unusually high may influence prosthetic valve positioning, coronary access after valve implantation, and the feasibility of future coronary interventions. Conversely, a low coronary ostium can be at risk of obstruction by displaced native or bioprosthetic leaflets. Therefore, preprocedural CT assessment remains essential when planning structural heart interventions [4, 22].

Implications for aortic root surgery and coronary reimplantation

Coronary ostial anatomy is equally important during aortic root replacement, valve-sparing root surgery, Bentall-type procedures, and other operations requiring mobilization or reimplantation of the coronary arteries. The surgeon must identify the precise position of each coronary ostium and maintain an appropriate relationship between the coronary buttons and the reconstructed aortic root. Variation in ostial height or circumferential position may alter the length and orientation of the coronary buttons and thereby influence postoperative coronary geometry [15].

The commissural findings of the present study are therefore particularly relevant to surgical anatomy. The concentration of right coronary ostia near Commissure I and the predominantly central or Commissure II-related position of left coronary ostia indicate that surgeons should not assume perfectly symmetrical coronary button positions. Individual preoperative imaging is preferable to relying on generalized anatomical expectations, particularly in patients undergoing complex aortic root reconstruction [15].

Potential relationship with coronary ostial disease

The relationship between ostial anatomy and coronary atherosclerotic disease has also been considered in previous anatomical studies. Alterations in local vessel geometry, flow direction, wall shear stress, and the transition between the aortic sinus and coronary artery may influence the distribution of atherosclerotic changes near the coronary origin [23, 24]. However, the present study did not assess atherosclerotic plaque, endothelial pathology, coronary flow, or clinical cardiovascular disease. Consequently, the current morphometric observations should be regarded as anatomical reference data rather than evidence of a causal association between ostial position and coronary artery disease.

Nevertheless, the wide range of ostial dimensions identified in the present series provides a useful foundation for future anatomical–clinical investigations. Combining cadaveric morphometry with CT coronary angiography, intravascular imaging, computational fluid-dynamic modelling, and clinical outcomes could determine whether ostial geometries are associated with altered local haemodynamic or increased susceptibility to ostial disease [1, 23, 24].

Population-related anatomical variation

Population-related anatomical variation is an important consideration when interpreting the morphology and morphometry of the coronary ostia. Previous cadaveric and anatomical studies have demonstrated variation in coronary ostial diameter, height, circumferential position, shape, and relationship to the aortic cusps and sinotubular junction (STJ) [1, 2, 7, 10, 13, 14, 25–27]. Studies conducted in Indian populations have also reported variation in the morphology and location of the coronary ostia, supporting the importance of population-specific anatomical data [1, 7, 25]. Similar observations have been reported in non-Indian populations, including Brazilian and West African populations, suggesting that coronary ostial morphology may demonstrate inter-population variability [2, 26]. Such differences may reflect a combination of genetic and developmental factors, demographic characteristics, sample composition, anatomical definitions, and differences in measurement methodology [16–20].

The present study demonstrates both similarities and differences in coronary ostial morphology when compared with previously published anatomical studies. In the present series, the mean ostial diameter was 4.78 mm for the right coronary artery (RCA) and 5.02 mm for the left coronary artery (LCA). Coronary ostial dimensions have previously been examined in cadaveric and morphometric studies, although reported measurements vary according to population and methodological approach [2, 7, 25, 27]. These findings emphasize the importance of considering population-specific morphometric values rather than applying a single reference range to all populations.

The vertical relationship of the coronary ostia to the aortic cusps also demonstrated a predominantly consistent pattern in the present study. The RCA ostium was located above the upper margin of the corresponding aortic cusp in 86.7% of specimens, whereas 90.0% of LCA ostia were located at the cusp level. Previous studies have described variable relationships between coronary ostia and the aortic valve cusps, with most coronary arteries arising from the corresponding aortic sinuses but with recognized variations in ostial height and position [1, 2, 7, 10, 13, 14]. The observed distribution in the present study is therefore broadly consistent with the established variability of coronary ostial anatomy.

With respect to the STJ, 81.7% of RCA ostia and 85.0% of LCA ostia were located below the STJ. The aortic root and STJ constitute important anatomical landmarks in determining the three-dimensional relationship between the coronary ostia, aortic valve, and ascending aorta [9]. Previous anatomical and imaging studies have emphasized the importance of assessing coronary ostial height in relation to the aortic root, particularly in the context of transcatheter aortic valve implantation (TAVI) and other aortic root interventions [5, 12, 22]. The predominantly sub-STJ position observed in the present study therefore

represents the expected anatomical relationship, while the minority of higher origins demonstrates the range of anatomical variation that may be encountered.

The circumferential distribution of the ostia also showed notable variation. In the present study, the RCA ostium was located near Commissure I in 58.3% of specimens, whereas 56.7% of LCA ostia were centrally positioned. Previous cadaveric studies have demonstrated variation in the topographical relationship of coronary ostia to the aortic valve cusps and commissures [1, 2, 7, 10, 14, 25, 27]. Such differences are anatomically relevant because the precise circumferential position of the ostium can influence its identification during anatomical dissection, coronary imaging, and procedures involving the aortic root.

A high coronary origin, defined in the present study as an ostium located above the STJ, was identified in 11.6% of RCA and 10.0% of LCA specimens. High coronary origins and other anomalous coronary configurations have been described in anatomical and clinical literature [11, 14, 21]. Although such findings represented a minority pattern in the present study, recognition of a high or atypically positioned coronary ostium is relevant during pre-procedural imaging and aortic valve interventions. Pre-procedural assessment of the spatial relationship between the coronary ostia and aortic valve/root is particularly important for evaluating the potential for coronary obstruction during TAVI [4, 12, 22].

The differences observed between the present study and previously published studies should, however, be interpreted cautiously. Variations in cadaveric age and sex distribution, sample size, population background, preservation methods, anatomical landmarks, measurement techniques, and definitions used for classifying ostial height or position may contribute to inter-study differences [1, 2, 7, 25–27]. Consequently, numerical differences between studies should not automatically be interpreted as evidence of true biological differences between populations. Rather, they may reflect a combination of biological variation and methodological heterogeneity.

From a clinical perspective, knowledge of coronary ostial dimensions, height, and position is relevant to selective coronary cannulation, coronary angiography, computed tomography (CT) assessment, TAVI, and surgical procedures involving the aortic root and coronary reimplantation [4, 5, 8, 12, 15, 22]. The relationship between coronary ostial height and the aortic valve has particular importance in TAVI because a low coronary origin and unfavorable aortic root geometry may contribute to the risk of coronary obstruction [4, 12]. Similarly, detailed knowledge of coronary ostial location is relevant during aortic root surgery and coronary reimplantation procedures [15].

The mean ostial heights observed in the present study were 13.70 mm for the RCA and 14.17 mm for the LCA. These measurements provide population-specific anatomical reference data and may contribute to the broader morphometric characterization of the aortic root and coronary arteries. However, because the present investigation was based on cadaveric morphology, these measurements should be interpreted as anatomical reference values rather than direct predictors of procedural outcomes. Their clinical application should be considered together with patient-specific imaging findings, particularly CT-based assessment of the aortic root and coronary anatomy [5, 22].

Overall, the present findings support the concept that coronary ostial anatomy exhibits both relatively consistent anatomical patterns and measurable inter-individual and inter-population variation. The present Indian cadaveric data complement previously reported anatomical observations [1, 7, 25] and contribute additional morphometric information regarding coronary ostial diameter, height, and position. Direct visualization of the aortic root, coronary ostia, cusps, commissures, and STJ in cadaveric specimens provides detailed anatomical information that complements angiographic and cross-sectional imaging studies [3, 22]. These findings may therefore serve as useful anatomical reference data for further anatomical, radiological, and clinical studies of coronary ostial morphology.

Strengths and limitations

A major strength of the present study is the direct assessment of the coronary ostia in cadaveric hearts using standardized anatomical landmarks and digital Vernier calipers. The simultaneous assessment of ostial diameter, cusp height, ostial height, STJ relationship, and commissural position provides a multidimensional description rather than relying on a single measurement. The exclusion of specimens with previous coronary intervention or cardiac surgery also reduces the likelihood that acquired procedural changes influenced the anatomical observations.

Several limitations should nevertheless be acknowledged. First, the study was performed on embalmed cadaveric specimens, and formalin fixation may alter tissue dimensions to some degree. Second, demographic information such as age and sex was unavailable, preventing subgroup analysis. Third, the study was descriptive and did not correlate the anatomical measurements with angiographic findings, clinical outcomes, catheterization difficulty, or TAVI-related events. Fourth, continuous measurements of the distance between each ostium and the STJ were not reported; consequently, ostia described as above the STJ should not automatically be classified as high-take-off coronary arteries according to a specific millimetric definition. Finally, the sample size provides useful anatomical information but may not fully represent variation in the broader population.

Future research should combine cadaveric morphometry with multidetector CT coronary angiography and three-dimensional reconstruction to assess ostial diameter, height, take-off angle, sinus dimensions, coronary-to-annulus distance, and valve-to-coronary relationships simultaneously. Such multimodal studies would allow anatomical measurements to be linked with clinically relevant outcomes, including catheter engagement, coronary obstruction during TAVI, surgical coronary reimplantation, and long-term coronary accessibility [1, 4, 22].

CONCLUSION

This study demonstrates considerable morphometric and positional variation in the coronary ostia, with the left coronary ostium generally larger than the right and most ostia located below the sinotubular junction. The observed differences in ostial height, diameter, and relationship to aortic cusps and commissures have important implications for coronary angiography, catheter-based interventions, aortic root surgery, CABG, and transcatheter aortic valve procedures. These anatomical data provide useful

reference values for pre-procedural planning and may help minimize procedural complications. Further imaging-based studies correlating coronary ostial morphology with clinical outcomes are warranted to strengthen its translational relevance.

Abbreviations

Abbreviation	Full form
CABG	Coronary Artery Bypass Grafting
CT	Computed Tomography
LCA	Left Coronary Artery
PCI	Percutaneous Coronary Intervention
RCA	Right Coronary Artery
STJ	Sinotubular Junction
TAVI	Transcatheter Aortic Valve Implantation

Declarations

Author Contribution

A.K. contributed to the conceptualization and supervision of the study, data curation, formal analysis, interpretation of the findings, manuscript preparation, and critical review and revision.

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Figures



Figure 1

Anatomical orientation of the aortic sinuses. (A) Transverse view of the tricuspid aortic valve showing the three aortic sinuses: 1, anterior aortic sinus; 2, right posterior aortic sinus; and 3, left posterior aortic sinus. (B) Schematic representation of the corresponding aortic sinuses: AAS, anterior aortic sinus; RPS, right posterior aortic sinus; and LPS, left posterior aortic sinus.

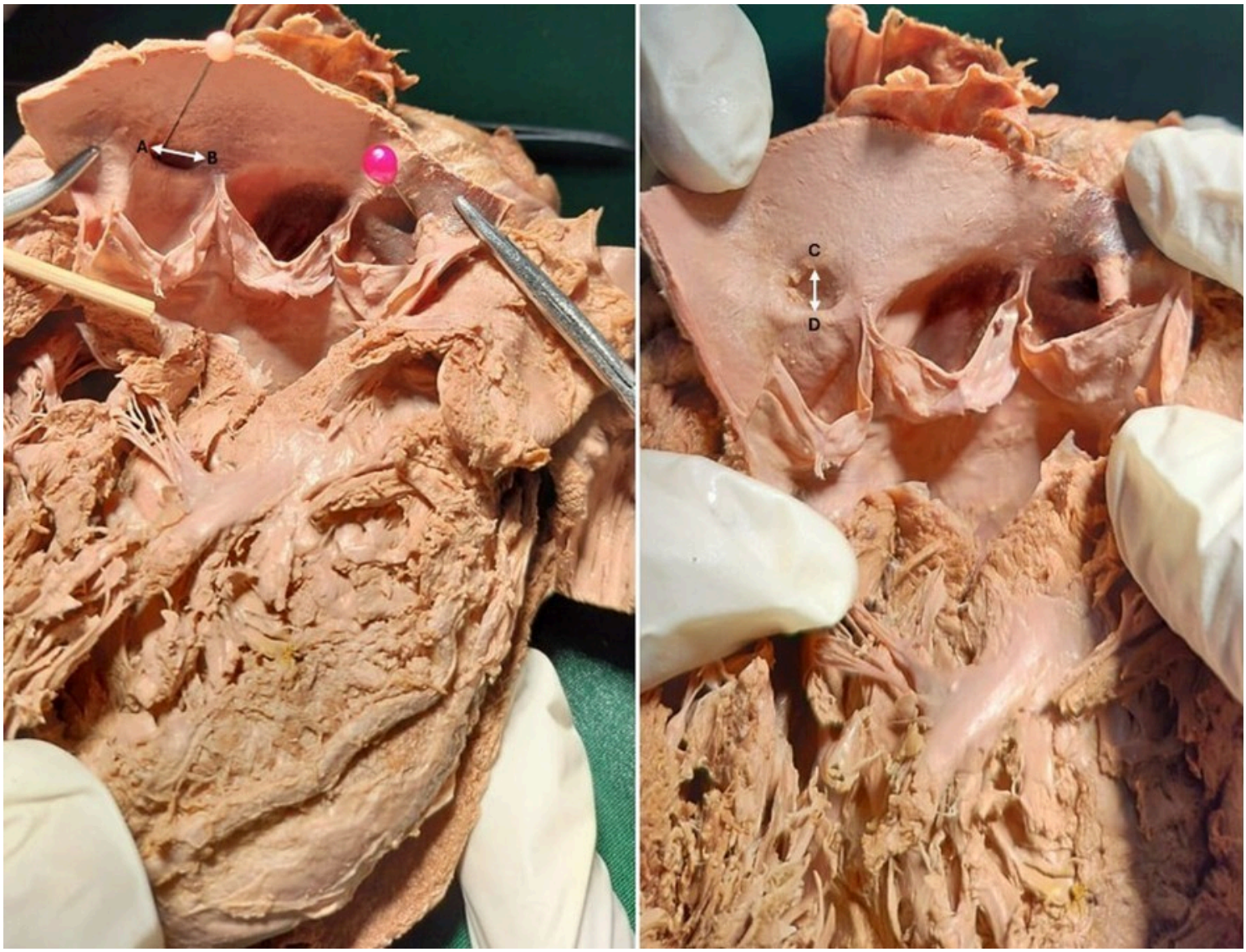


Figure 2

Photograph showing the ostium of the coronary sinus in the wall of the right atrium. AB indicates the transverse diameter, and CD indicates the vertical diameter of the coronary sinus ostium.

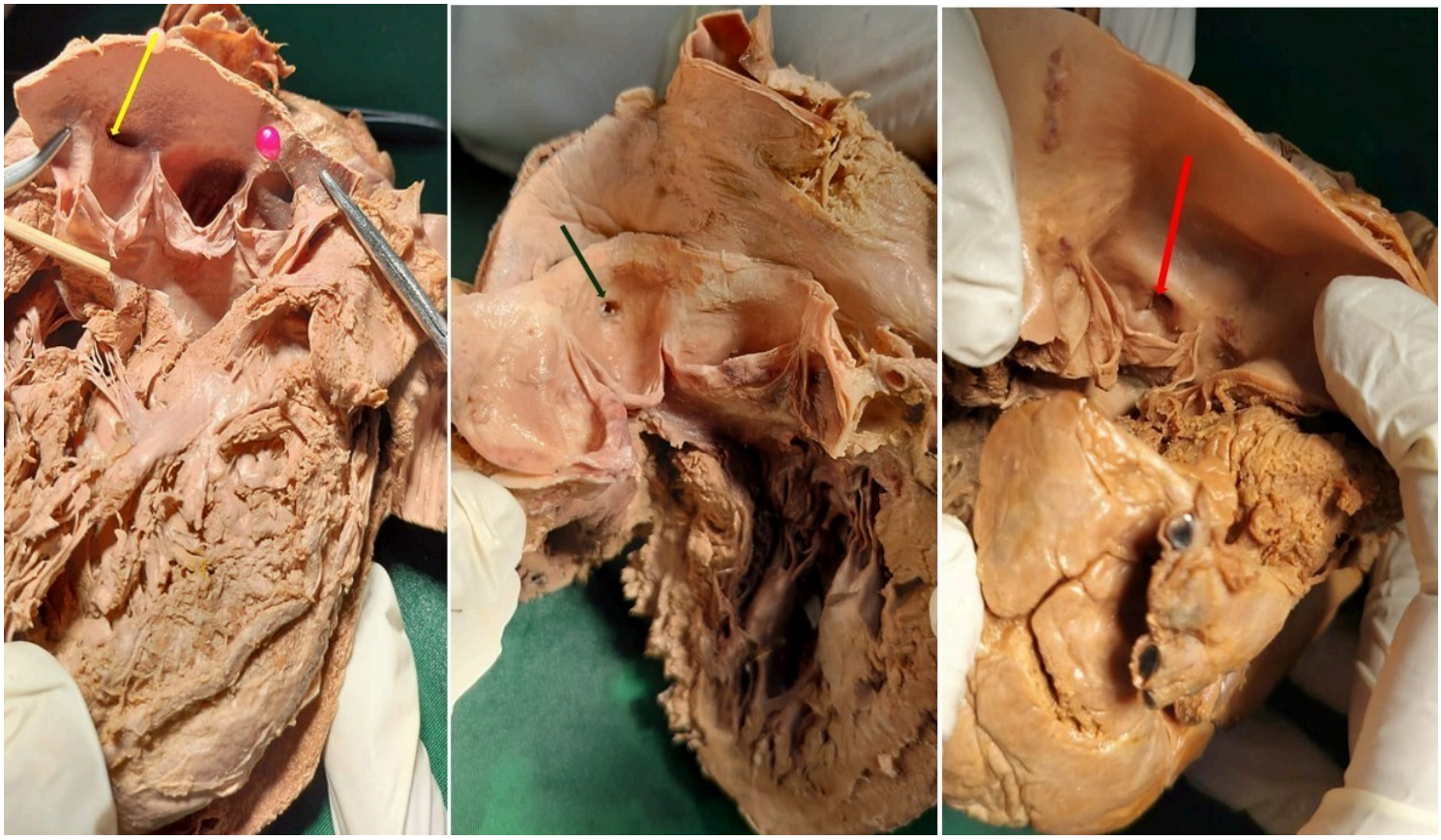


Figure 3

Location of the coronary ostia in relation to the aortic commissures. Yellow arrow indicates an ostium located above the commissure; black arrow indicates an ostium located below the commissure; red arrow indicates an ostium located at the level of the commissure.

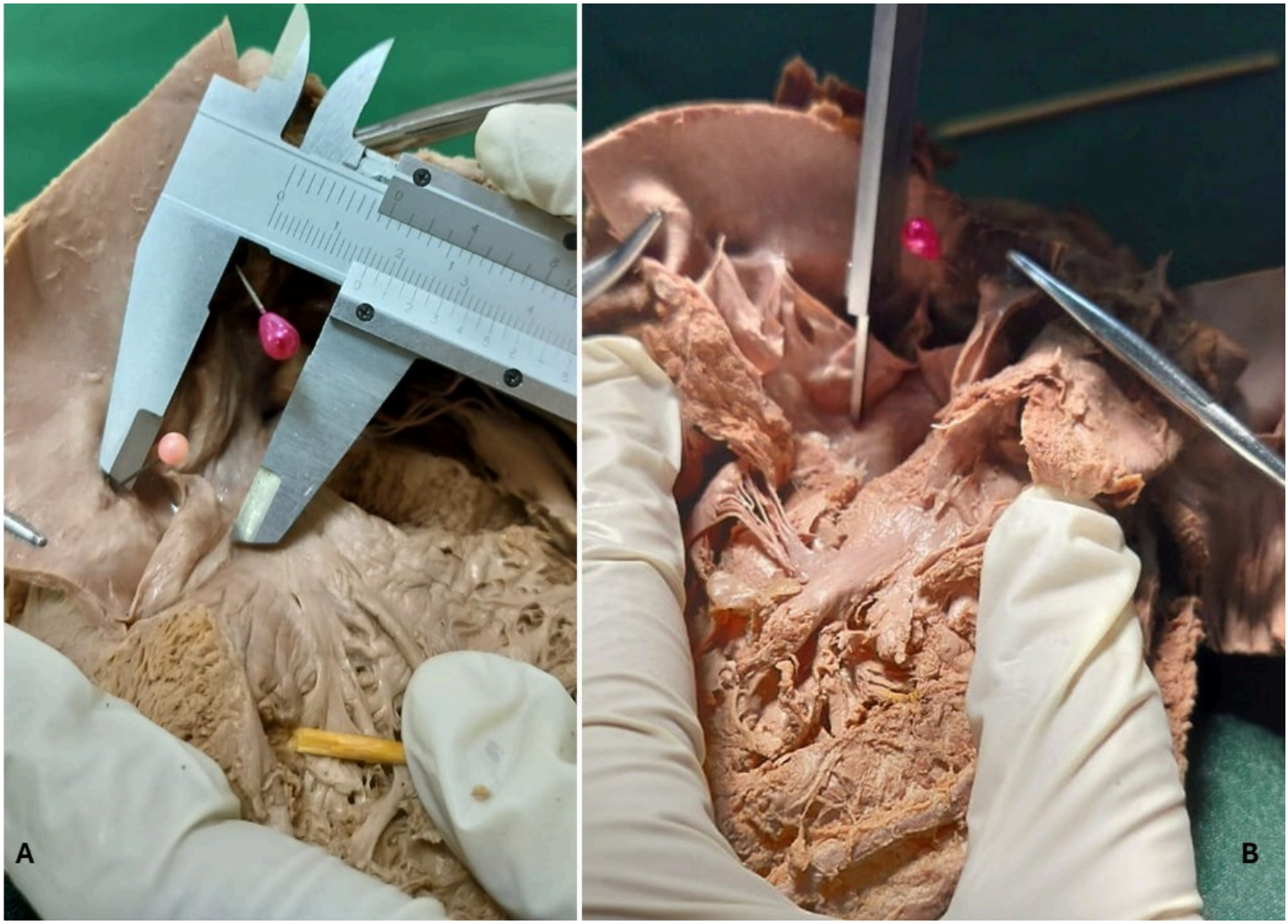


Figure 4

Photographs demonstrating the vertical measurements of the coronary ostium and aortic cusp: (A) vertical height of the coronary ostium from the reference level of the aortic annulus; and (B) height of the corresponding aortic cusp.