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Morphological Variations of the Left Coronary Artery: A Cadaveric Study

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Abstract

Background/Objectives: Ischemic injury resulting from the blockage of the left coronary artery or its terminal left anterior descending and circumflex branches is associated with relatively high rates of morbidity and mortality. Variations in left coronary artery size and the number of terminal branches may in part influence the development of such blockages due to altered intraluminal fluid dynamics, while also potentially complicating medical imaging interpretation or preoperative planning for interventions of coronary circulation. While left coronary artery morphology has been extensively reported on, the results reveal substantial geographical variability, with the Eastern United States being largely underrepresented. **Methods:** We aimed to establish baseline measurements of left coronary artery length and width and the prevalence of variable branching patterns by examining 101 cadaveric hearts from adult, whole-body donors (59 F, 42 M) that were ethically willed to the State of Virginia. **Results:** The most common terminal branching pattern was left coronary artery bifurcation (n = 54), followed by trifurcation (n = 45), tetrafurcation (n = 1), and aberrant circumflex artery origin, with the left coronary artery traveling in the anterior interventricular sulcus without branching (n = 1). Compared to females, the left coronary artery of males was significantly longer ($\bar{x}$ = 14.87 mm ± 5.73 mm vs. $\bar{x}$ = 12.64 mm ± 4.79; p = 0.04) and wider ($\bar{x}$ = 6.31 mm ± 1.10 mm vs. $\bar{x}$ = 5.54 mm ± 0.90 mm; p < 0.01), regardless of terminal branching pattern. **Conclusions:** These results can support the interpretation of coronary angiograms and the preoperative planning of surgical interventions involving coronary vasculature.

Keywords: left coronary artery; anterior interventricular; left anterior descending; circumflex artery; coronary angiography; anatomical variation; ramus intermedius artery

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1. Introduction

The left coronary artery (LCA) most often arises from the left aortic sinus before traveling a short distance between the left auricle and pulmonary trunk, then finally terminating by bifurcating into the circumflex artery (Cx) and left anterior descending artery (LAD; also known as the anterior interventricular artery). Collectively, the LCA and its branches supply between 63.8 and 77.5% of myocardial territory, encompassing the interventricular septum, apex, and anterior ventricular walls [1,2], though this may vary depending on coronary dominance [3].

Understanding LCA distribution is imperative in the management of cardiac ischemic injury since the LAD and Cx are among the most common sites for cardiovascular lesions.

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Studies on Saudi Arabian patients with myocardial infarction found the involved vessel to be LAD and Cx in 42.5% and 19.1% of cases, respectively. These rates respectively rose to 82.4% and 85.3% in patients with multi-vessel involvement [4,5]. Similar rates have been found in the United States of America [6], India [7], and Poland [8]. Notably, the risk for acute vessel occlusion has been shown to diminish by 30% and 26% for the LAD and Cx, respectively, with each 10 mm increment from the vessel origin, making the LCA bifurcation point particularly clinically salient [6].

Initial work-up for cardiac ischemic injury may involve myocardial perfusion imaging to localize ischemic territory, though the accuracy of traditional methods in assigning coronary vessels to injured myocardium has been shown to be hindered in patients with variable coronary branching patterns [9]. While more contemporary methods using quantitative coronary angiography permit higher fidelity, three-dimensional visualization of the coronary arterial tree, inherent technological limitations may omit critical areas, including the LCA bifurcation [10]. Aberrant LCA morphology may therefore complicate clinical management of cardiac interventions involving coronary circulation, such as coronary artery bypass grafting and coronary catheterization.

LCA variations include supernumerary branches at its termination, where LAD and Cx are accompanied by at least one ramus intermedius artery (RI). In addition to potentially hindering coronary angiography interpretation, RIs complicate the intraluminal geometry at the LCA terminus. This may perpetuate atherosclerotic plaque formation via increased oscillatory, turbulent flow along the carinal walls, and lower endothelial shear stress along the inner aspects of the peripheral walls [11]. Additionally, the LCA may be altogether absent, with LAD and Cx arising independently from the left aortic sinus. Absent LCA has been associated with a higher incidence of myocardial bridging and left-dominant coronary circulation, as well as increased difficulty with Cx cannulization [12]. Rarer still is an anomalous Cx origin from the right coronary artery (RCA), with the Cx taking a retro-aortic course to reach the coronary sulcus. This variation may be vulnerable to damage during valve replacement procedures, serve as a poor target for coronary artery bypass grafts, and be more susceptible to atherosclerosis, particularly in the retro-aortic portion [13–15].

The prevalence of these LCA variations has been reviewed previously and revealed substantial heterogeneity across geographical locations, though the Mid-Atlantic and Appalachian regions remain largely underrepresented [16]. To address this, LCA morphology was examined in a sample of anatomical donors that voluntarily willed their bodies to the state of Virginia for academic and scholarly purposes. The relationship between LCA termination patterns with biological sex, as well as LCA width and length, were observed. The results of this study can support diagnostic imaging interpretation and preoperative planning in the treatment of myocardial ischemic injury.

2. Materials and Methods

2.1. Ethical Approval

This work was reviewed and approved by the Edward Via College of Osteopathic Medicine (VCOM) Institutional Review Board (reference #2022-067) and was conducted in accordance with the Declaration of Helsinki.

2.2. Study Design and Donor Recruitment

This study employed a descriptive, cross-sectional design to investigate LCA morphology in adult whole-body donors.

Donors who willfully donated their bodies to VCOM for academic and research purposes were recruited to the study via convenience sampling. Inclusion criteria consisted of consent from the donor for their tissue to be used for research. Exclusion criteria included surgical history of coronary circulation (e.g., coronary artery bypass grafting) that included the LCA or damage to the LCA during dissection.

2.3. Dissection Protocol

Cadaveric dissection was carried out on whole-body adult donors that were willed to VCOM via the Virginia State Anatomical Program or the Anatomical Gift Program of the University of Massachusetts.

Hearts were exposed and removed via sharp dissection as part of the first-year osteopathic medical school curriculum. Briefly, exposure was achieved via thoracotomy and excision of the pericardium, and the great vessels were then cut to release the heart from the pericardial cavity. Coronary vasculature was exposed with removal of the epicardial adipose tissue.

2.4. Data Collection

The number of terminal branches of the LCA were determined by counting the vessels arising from within 0.5 cm of the LCA carina (Figure 1).

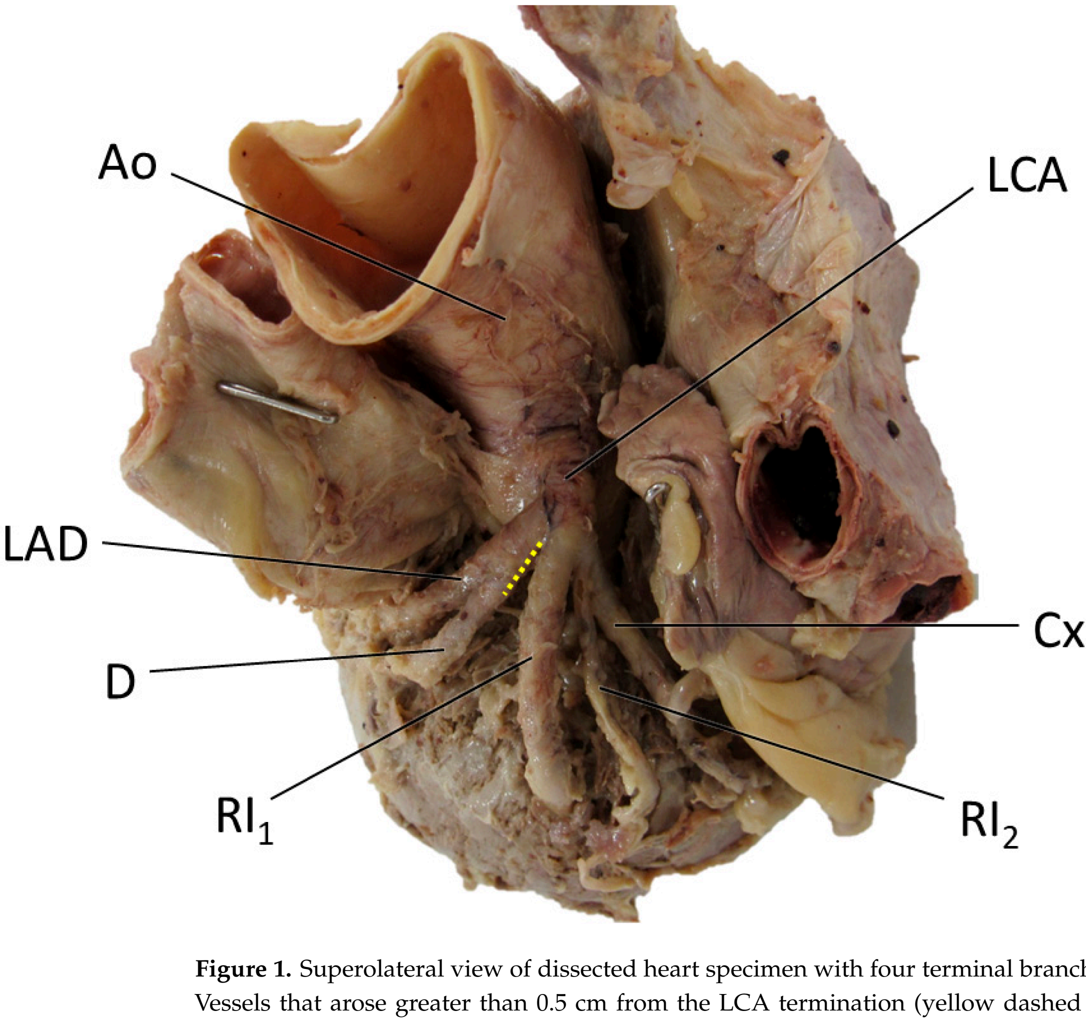

Figure 1. Superolateral view of dissected heart specimen with four terminal branches of the LCA. Vessels that arose greater than 0.5 cm from the LCA termination (yellow dashed line) were not considered a terminal branch of the LCA. Ao, aorta; Cx, circumflex artery; D, diagonal branch; LAD, left anterior descending artery; LCA, left coronary artery; RI1, first ramus intermedius branch; RI2, second ramus intermedius branch.

Neiko digital calipers (model #01407A) and string were used to measure the length and diameter of the LCA in triplicate. Length was measured from the aortic wall to the LCA termination. Diameter was measured immediately proximal to the terminal branching of the LCA. The average of the triplicate measurements was used for data analysis. Coronary dominance was determined by identifying the posterior interventricular artery as arising from either the RCA or LCA (via Cx).

2.5. Statistical Analysis

Prior to inferential analyses, normality was assessed using Shapiro–Wilk tests. Differences in the length and diameter of the LCA in males versus females as well as in LCAs that terminated by bifurcating versus trifurcating were evaluated using Welch's independent-sample *t*-tests, which are robust to unequal variances and moderate deviations from normality. Chi-square analysis was used to test for significant differences in the rates of bifurcating and trifurcating LCAs in males versus females, and in right versus left coronary dominance. Statistical significance was determined at the 0.05 alpha level. All statistical tests were calculated in RStudio (version 2025.09.2; PBC, Boston, MA, USA).

3. Results

A total of 101 adult subjects (59 F, 42 M) were included in the study, with demographic information summarized in Table 1. One female subject had an aberrant Cx that arose from the RCA and took a retro-aortic course to reach to the coronary sulcus. The LCA arose from the left aortic sinus and continued in the anterior interventricular sulcus without branching. Further description of this case is provided elsewhere [17]. One other female subject had a LCA terminate into four branches: Cx, LAD, and two RI branches (Figure 1).

Table 1. Demographic information of included subjects.

Sex	*n*	Average Age (Years) [Range]
Female	59	85.39 [66–102]
Male	42	83.73 [59–101]
Total	101	84.70 [59–102]

The remaining 99 subjects either demonstrated a bifurcating or trifurcating LCA. LCA bifurcation was seen in 54 subjects (35 F, 19 M) (Figures 2A and 3A), while trifurcation was seen in 45 subjects (22 F, 23 M) (Figures 2B and 3A). The rates of bifurcating versus trifurcating LCAs in males versus females were not significantly different ($X^2 = 2.54$; degrees of freedom: 1; $p = 0.11$).

Results for length and diameter measurements are described as mean ($\bar{x}$) ± standard deviation (Table 2, Figure 3). There was no statistically significant difference in the length of bifurcating and trifurcating LCAs ($p = 0.44$). When grouped by sex, males collectively had a significantly longer LCA compared to females ($\bar{x}$ = 14.87 mm ± 5.73 mm and $\bar{x}$ = 12.64 mm ± 4.79 mm, respectively; $p = 0.04$) (Figure 3B). There was no statistically significant difference in LCA diameter between bifurcating and trifurcating individuals ($p = 0.97$); however, when grouped by sex, males had a significantly wider LCA than females ($\bar{x}$ = 6.31 mm ± 1.10 mm and $\bar{x}$ = 5.54 mm ± 0.90 mm, respectively; $p < 0.01$) (Figure 3C). Shapiro–Wilk tests indicated departures from normality; however, results were robust across parametric and nonparametric analyses (Table S1).

Results of the coronary dominance calculations are summarized in Table 2. Of the 12 hearts that had left-dominant coronary circulation, four had bifurcating LCAs and eight had trifurcating. Of the 86 hearts that had right-dominant coronary circulation, 50 had a bifurcating LCA and 36 had trifurcating. One heart with a trifurcating LCA exhibited a co-dominant coronary circulation. Chi-square analysis revealed no statistically significant difference in right versus left coronary dominance in bifurcating versus trifurcating LCAs ($X^2 = 2.62$; degrees of freedom: 1; $p = 0.10$).

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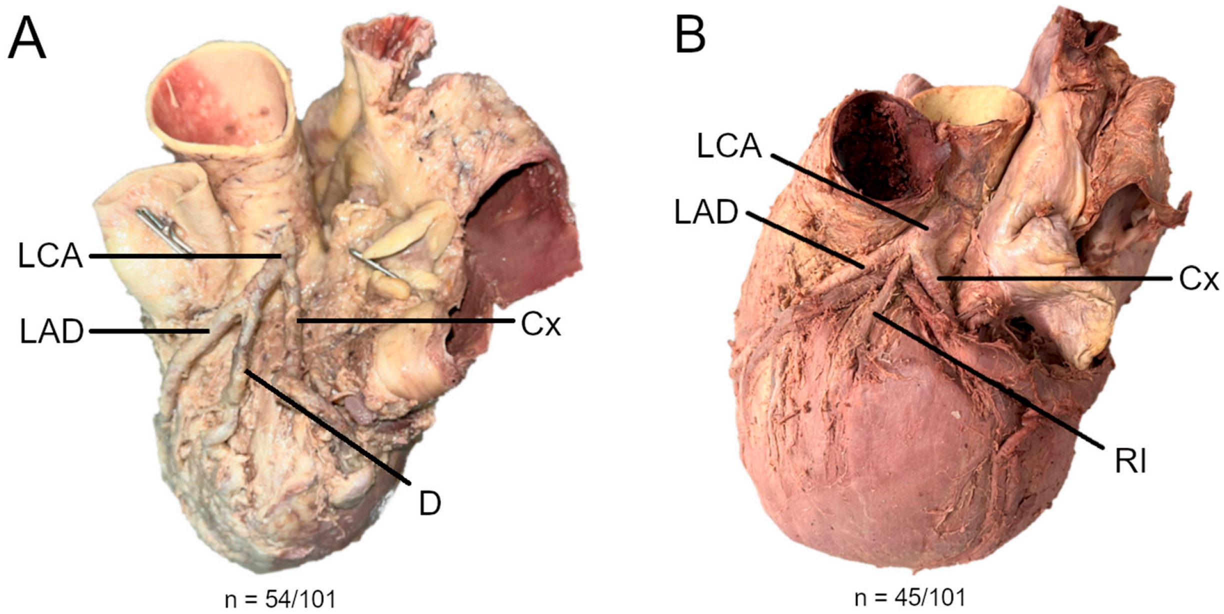

Figure 2. Cadaveric heart specimens. (**A**) Bifurcating LCA was seen in 54/101 hearts. (**B**) Trifurcating LCA was seen in 45/101 hearts. The remaining specimens had LCAs that terminated via tetrafurcation (n = 1) or an unbranched LCA with aberrant Cx origin (n = 1). Cx, circumflex artery; D, diagonal branch; LAD, left anterior descending; LCA; left coronary artery; RI, ramus intermedius branch.

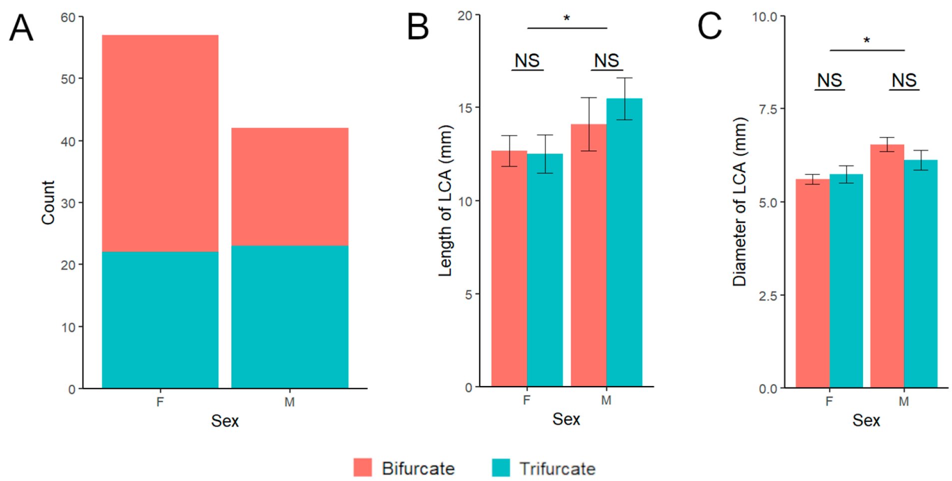

Figure 3. Measurements of bifurcating and trifurcating LCAs. (**A**) Number of bifurcating and trifurcating LCAs in females and males. (**B**) Differences in LCA length in males versus females and in bifurcating versus trifurcating LCAs. (**C**) Differences in LCA diameter in males versus females and in bifurcating versus trifurcating LCAs. F, female; LCA; left coronary artery; M, male; NS, non-significant; *, $p < 0.05$.

Table 2. Breakdown of results between LCAs that terminated via bifurcation versus trifurcation.

	Sex (n)			LCA Length (mm)		LCA Diameter (mm)		Coronary Dominance	
	F	M	p	[$\bar{x} \pm$ SD]	p	[$\bar{x} \pm$ SD]	p	[L:R:Co]	p
Bi	35	19	0.11	13.2 ± 5.37	0.44	5.94 ± 0.91	0.97	4:50:0	0.10
Tri	22	23		14.04 ± 5.27		5.93 ± 1.19		8:36:1	
Total	57	42		13.58 ± 5.31		5.94 ± 1.04		12:86:1	

Bi, bifurcation; Co, co-dominant; F, female; L, left-dominant; LCA, left coronary artery; R, right-dominant; SD, standard deviation; Tri, trifurcation.

4. Discussion

This study aimed to describe the potential influence of biological sex and terminal branching patterns on the morphology of the LCA. The results revealed biological sex to be associated with differences in LCA length and width within the studied sample, with males having a longer and wider LCA than females, regardless of the terminal branching pattern (Figure 3).

The main trunks of trifurcating LCAs were found to be generally longer (14.04 ± 5.27 mm) than those that bifurcated (13.2 ± 5.37 mm), though this relationship was not statistically significant (p = 0.44). This mirrors the findings of dissection studies out of Bosnia and Herzegovina [18] and Brazil [19], with the latter reaching statistical significance. This was further supported by a medical imaging study that analyzed LCA morphology in 1500 computed tomography (CT) scans and reported that long LCAs (>15 mm) were associated with decreased rates of bifurcation [20]. These findings can possibly assist in the care of patients with heart disease, as there is evidence to suggest that a short LCA may be a risk factor in developing coronary atherosclerosis [21]. Other CT angiogram studies have found that patients that express trifurcation due to the presence of a single RI had higher levels of troponin (69.3 ± 39.9 ng/dL in the RI group vs. 50.3 ± 39.2 ng/dL in the non-RI group; p = 0.01) and creatine kinase-MB levels (277.3 ± 270.6 ng/dL in RI group vs. 174.5 ± 189.9 ng/dL; p = 0.01) in the context of myocardial infarction [22]. The influence of LCA length and termination pattern on health outcomes therefore remains unclear and is likely multifaceted.

Examining the results of this study through a global lens can help reveal geographical trends in LCA patterning (Table 3). In the Midwest region of the United States, Baptista et al. conducted a study comparing bifurcation and trifurcation between both males and females as well as White populations and non-White populations [23]. It was found that within the male populations, the rate of trifurcation was similar among Whites and non-Whites (36.6% and 37.1%, respectively). When comparing white females to non-white females, however, it was revealed that white women expressed trifurcation 34.4% of the time, whereas 60% of non-white women expressed trifurcation [23]. Within South America, studies of Brazilian subjects found that 46.0–52.28% of subjects had trifurcating LCAs [19,24,25], while a trifurcation rate of 42.2% has been seen in Colombian subjects [26]. These rates of LCA trifurcation in South American studies, as well as the results reported here in this current study (45%), are generally higher than those reported out of Bosnia and Herzegovina (29%) [27], India (16%) [28], Egypt (30.3%) [29], Thailand (16%) [30], and China (25%) [20]. However, these studies are limited by small sample sizes, omit ancestral or genetic information, and lack standardized methodology. Therefore, this is meant to serve as a simple exploration of geographical differences in LCA morphology that may inform more sophisticated, hypothesis-driven analyses in subsequent studies.

An exploration of geographical heterogeneity with a larger sample size that is able to incorporate ancestral information from subjects representing a broad range of geographical locations would better reveal any global trends in LCA morphology. Study methodology should also be considered since greater rates of LCA bifurcation are seen in medical imaging studies (75.79%) compared to dissection studies (64.22%) [16]. Further, defining terminal branches of the LCA using quantitative metrics, as described herein but often omitted from similar studies, would help to support cross-study comparisons and reproducibility.

This study used a distance threshold of 0.5 cm from the LCA terminal carina as a standard metric for RI identification. This metric was based on the definition of RI offered in a previous study of the coronary tree, describing the 0.5 cm measurement as the preferred definition used by cardiologists [31]. While employing this quantitative approach helped eliminate bias and promote reproducibility, alternative or absent standardized approaches

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in prior studies limit cross-study comparisons. A measurement of 1 cm has been used as a cutoff in anatomical studies describing branching of the cerebral vasculature [32] and in the clinical definition of "high takeoff" coronary vessels [33]; however, a standard measurement or quantitative definition is most often missing from anatomical studies of LCA branching patterns [19,20,23,27]. In future studies, incorporating a distance threshold of 0.5 cm as a standardized RI definition would better support a comparison of the results across studies and populations while also aligning with the definition used by cardiologists [31].

Table 3. A global perspective of left coronary artery (LCA) trifurcation rates.

Study Location	Rates of LCA Trifurcation
Bosnia and Herzegovina [27]	29%
Brazil [19,24,25]	46.0–52.28%
China [20]	25%
Colombia [26]	42.2%
Egypt [29]	30.3%
India [28]	16%
Thailand [30]	16%
United States	
Midwest [23]	Similar between white (36.6%) and non-white (37.1%) males Notably lower in white (34.4%) versus non-white (60%) females
Eastern [this study]	45%

The results of this study should be cautiously interpreted in the context of the demographic details of our sample. The comparison of our male and female subjects suggested a degree of sexual dimorphism in LCA morphology, with males having wider and longer LCAs compared to females (Figure 3). However, our lack of anthropometric data (e.g., height, weight, body mass index) did not allow us to determine the influence of overall body size on LCA size, limiting the significance of these findings. Notably, males have been previously shown to have larger LCAs compared to females, even when controlling for body size [34], though body size has been shown to have a greater influence than sex on coronary arterial size [35]. Further, the average age of our sample was 84.70 years. Advanced age has been shown to be associated with altered hemodynamic parameters [36] that may lead to remodeling of the coronary microvasculature [37]. In addition to such age-related changes, a history of cardiovascular medical conditions (e.g., hypertension, diabetes mellitus, coronary artery disease, heart failure), which is not provided as part of the donation process, could have feasibly influenced the length and width of the LCA in this sample.

This study was not without limitations. The interpretation of the results should be considered in the context of our relatively small sample size. This was also a single-institution study, further limiting the generalizability of the results to other regions or populations. Since our subjects were adults from a single geographical location, and ancestral data was not included, extrapolation of the results to other regions, populations, or age groups is limited. The absence of ancestral data from this and other similar studies is particularly limiting for cross-study comparisons. Ancestral data would need to be incorporated in future iterations if geographical patterns of LCA morphology are to be fully elucidated. Future studies should also look to explore variations in the remaining components of the coronary circulation (e.g., RCA), and the inclusion of a proxy for body size (e.g., height or body mass index) would help elucidate the influence of overall body size on coronary artery morphology. Relevant cardiovascular medical history, and the potential influence on remodeling of coronary vasculature, should also be considered and controlled for where possible. Finally, length and width measurements, as well as the numbering of terminal branches, may have been subject to human error, particularly in LCAs that were markedly tortuous. While taking length and width measurements in triplicate can help curb the influence of measurement inaccuracies, we acknowledge this as a potential source of error.

5. Conclusions

This dissection study of 101 cadaveric hearts found the LCA to be significantly longer and wider in males than females, regardless of terminal branching pattern. The most common terminal branching pattern was the LCA bifurcating into LAD and Cx (53%), followed by trifurcation into LAD, Cx, and a single RI (45%); tetrafurcation into LAD, Cx, and two RIs (1%); and aberrant Cx origin, with the LCA traveling in the anterior interventricular sulcus without branching (1%). These results can be used to support medical imaging interpretation and preoperative planning for coronary artery bypass grafts and coronary catheterization to promote positive patient outcomes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/anatomia5030017/s1, Table S1: Summary of group comparisons using Welch's two-sample *t*-test (parametric) and Mann-Whitney U test (non-parametric).

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the Edward Via College of Osteopathic Medicine (reference #2022-067, date: 14 September 2022).

Informed Consent Statement: Informed consent for donor tissue to be used for research purposes was obtained from all subjects at the time of donation.

Data Availability Statement: Data will be made available upon reasonable request to the corresponding author, A.W.B.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CT	Computed tomography
Cx	Circumflex artery
LAD	Left anterior descending artery
LCA	Left coronary artery
RI	Ramus intermedius

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