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Anatomical Variations of Coronary Arteries and Their Clinical Implications: A Systematic Review

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ABSTRACT

Coronary artery anatomical variations range from benign incidental findings to potentially life-threatening anomalies. The increasing use of coronary computed tomography angiography (CCTA) has improved their detection, anatomical characterization, and clinical assessment. **Objectives:** To systematically identify major coronary artery anatomical variations and evaluate their clinical implications, particularly in distinguishing benign variants from high-risk anomalies. **Methods:** This systematic review followed the PRISMA 2020 guidelines. The PubMed, Web of Science, and Scopus databases were searched from January 2020 to December 2025. Studies reporting coronary artery anatomical variations in humans were included if they were primary studies reporting clinical implications. Reviews, systematic reviews, meta-analyses, case reports, case series, pilot studies, and non-human studies were excluded. The studies were screened and data extracted by two reviewers independently. **Results:** Eleven studies were included. Right coronary dominance was the most common dominance pattern. Myocardial bridging was the most frequently reported course variation, whereas coronary artery fistulae were uncommon. Interarterial and intramural courses were associated with the greatest clinical risk, including myocardial ischemia, syncope, arrhythmias, and sudden cardiac death. Most other variations were benign but remained important during catheterization and cardiac surgery. **Conclusions:** Most coronary artery variations are benign, whereas clinically significant anomalies are uncommon. Their prognostic importance depends primarily on the anatomical origin and proximal course. CCTA supports accurate characterization, risk stratification, and individualized clinical management.

INTRODUCTION

The coronary circulation is complex and highly variable between individuals, as illustrated in the coronary artery anatomy. These differences can refer to the beginning, course, branching, dominance, or end of the coronary arteries. Many of these variants are silent and asymptomatic, but some can cause disturbances in coronary blood flow or anatomically pose a high risk for interactions with neighbouring cardiovascular structures, which may lead to myocardial ischaemia, arrhythmia, syncope or sudden cardiac death [1]. Many of these variations have been found at autopsy or during invasive coronary angiography in the past. But, with the advances in the use of non-invasive imaging, especially coronary computed tomography angiography (CCTA), the detection and anatomical description of coronary artery variation have improved significantly [2, 3]. CAs are a relatively uncommon finding in the general population, but their clinical significance can be significant, especially when the patient is young or middle-aged and has cardiac symptoms that are unexplained [4, 5]. The clinical significance of

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anatomical anomalies like myocardial bridging, interarterial coronary courses, high take-off coronary arteries, separate coronary ostia, and coronary fistulae vary widely. Some may be incidental findings; others are linked to exertional chest pain, myocardial ischemia, syncope, arrhythmias, or sudden cardiac death, even in the absence of obstructive atherosclerotic coronary disease [6]. Generally, coronary artery fistulae are rare and non-symptomatic; however, larger fistulae can lead to myocardial ischemia, arrhythmias, or heart failure due to changes in coronary hemodynamics [7]. The clinical significance of the coronary abnormalities, therefore, is not only whether there is an abnormality, but also how they occur, whether they cause an obstruction, the relationship of the coronary abnormalities to the great vessels, and whether they cause or may cause a decrease in blood supply to the coronary vessels. It is especially significant for the cardiologist, radiologist, interventional cardiologist, and cardiac surgeon to differentiate the benign variations from the clinically important coronary anomalies. Selective coronary catheterization, percutaneous coronary intervention, coronary artery bypass, and cardiac valve surgery may be challenging due to abnormal coronary origin or course [8]. In patients who develop exertional symptoms or myocardial ischemia on functional assessment, a high-risk coronary anatomy may require more intensive monitoring, modification of activity, or surgical correction [9, 10]. With the development of CCTA, the coronary ostium, course of the vessels in the heart, branching pattern, and the relationship of anomalous vessels with the aorta and pulmonary artery can be evaluated in detail. The use of CCTA is also useful for the detection of less frequent branching patterns, such as a dual left anterior descending coronary artery, that can be relevant for interventional and surgical planning [11].

Although there have been many imaging and anatomic studies, there are still significant unknowns about the actual range and significance of coronary artery variations. There are wide variations in the frequencies reported between different populations, study designs, diagnostic modalities, and the definitions of coronary abnormalities. Besides, there are benign anatomic variants and potentially life-threatening anomalies; not all of these variants are clearly distinguished when discussing their clinical implications. This leaves clinicians with uncertainty about which variations are ones that simply don't need further evaluation or intervention, which ones should receive more functional evaluation or follow-up, and which ones may need interventional or surgical treatment. As the use of CCTA has grown, so has the number of incidental coronary variations, which has led to a need for a new synthesis of anatomic variants, based on their true clinical relevance. Hence, a systematic review of current evidence regarding coronary artery anatomical variants was required, along with the integration of data from various populations and diagnostic techniques. This is a systematic review to identify and describe the important coronary artery variations and explore the reported clinical relevance. Also, to differentiate the commonly encountered benign variants from higher-risk anomalies of diagnostic, prognostic, interventional, or surgical significance.

METHODS

This systematic review was conducted to identify and synthesize contemporary evidence regarding anatomical variations of the coronary arteries and their associated clinical implications. The review methodology was developed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparent, structured, and reproducible reporting of the study-selection process. Because substantial clinical and methodological heterogeneity was anticipated across study populations, designs, imaging modalities, definitions of coronary variations, and reported outcomes, a qualitative systematic synthesis was planned, and no meta-analysis was performed. A comprehensive literature search was conducted in PubMed, Web of Science, and Scopus for studies published from January 2020 to December 2025. The search strategy incorporated relevant keywords and Medical Subject Headings (MeSH), including "coronary artery anomalies," "coronary artery variations," "anomalous coronary origin," "coronary dominance," "myocardial bridging," "coronary artery fistula," and "clinical significance." Boolean operators AND and OR were used to combine related terms. A representative search strategy was: ("coronary artery anomalies" OR "coronary artery variations" OR "anomalous coronary origin" OR "coronary dominance" OR "myocardial bridging") AND ("clinical significance" OR "clinical implications" OR "cardiac outcomes"). Search terms were adapted, where necessary, according to the indexing system and search interface of each database. In addition, the reference lists of potentially eligible and included articles were manually screened to identify further relevant studies that might not have been retrieved through the electronic database search. Primary human studies reporting anatomical variations of the coronary arteries were considered eligible irrespective of whether they used cross-sectional, retrospective, prospective, cohort, angiographic, CCTA, other CT-based imaging, or cadaveric study designs. To be included, a study was required to report at least one clearly defined coronary artery anatomical variation and provide information regarding its anatomical characteristics and/or clinical implications. Studies published within the

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predefined search period and available in sufficient full-text form for assessment were considered for inclusion. Case reports, case series, pilot studies, narrative reviews, systematic reviews, meta-analyses, editorials, conference abstracts, and non-human studies were excluded. Studies that did not provide relevant information regarding coronary artery anatomy or its clinical significance were also excluded. The data were then extracted from the three databases and exported to a reference-management system, where duplicate records were identified and removed before screening. Titles and abstracts were then screened independently by two reviewers based on the pre-established criteria for eligibility, after the deduplication process. Full-text articles were obtained for thorough review of potentially relevant articles selected by either reviewer. A full-text article assessment followed, conducted independently by the assessors, against the inclusion/exclusion criteria. Disagreements between the two reviewers around eligibility were discussed, and consensus was reached before the final decision as to eligibility for the studies was made. The entire identification, screening, eligibility, and inclusion process was reported with the PRISMA 2020 flow diagram. Database searching (PubMed n=178, Web of Science n=156, and Scopus n=178) identified a total of 512 records. A total of 378 were screened by title and abstract, after which 295 were excluded based on their title or abstract. Eighty-three Reports were requested for retrieval, and seven were not retrieved. Hence, all 76 full-text reports were evaluated for eligibility, with a total exclusion of 65 reports. Lastly, there were 11 studies that fulfilled the eligibility criteria and were included in the qualitative synthesis (Figure 1).

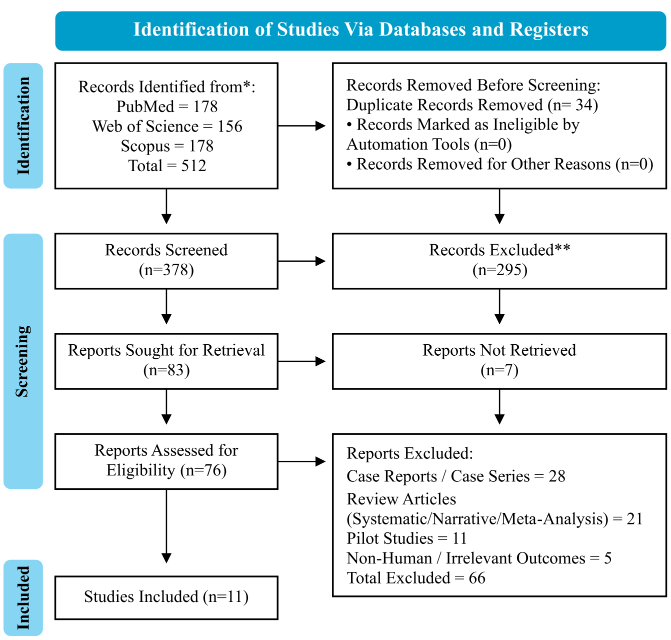

Figure 1: PRISMA 2020 Flow Diagram of Study Selection Process

Data from the eligible studies were extracted using a standardized data-extraction form. The variables collected included first author, year of publication, country, study design, sample size, diagnostic or anatomical assessment modality, coronary dominance pattern, type of coronary artery variation, abnormalities of coronary origin or course, myocardial bridging, coronary fistulae, other reported anatomical variants, clinical presentation, and reported clinical implications. Extracted information was cross-checked between the reviewers to minimize transcription errors and ensure consistency with the original studies. Any discrepancies identified during data extraction were discussed and resolved before preparation of the final evidence tables. A modified Newcastle-Ottawa Scale (NOS) was used to evaluate the methodological quality of the observational studies included. Three main domains were assessed: (1) selection of the study population; (2) comparability of study groups or control of relevant confounding variables; and (3) the assessment of outcomes or anatomical findings. The total points that could be scored were 9. Research studies that received a score of 7-9 points were considered to be at low risk of bias, 4-6 points were considered to be at moderate risk of bias, and 0-3 points were considered to be at high risk of bias. A summary of each included study's risk of bias was provided and integrated into a summary of the evidence as a whole. Because of substantial heterogeneity in study designs, study populations, diagnostic modalities, definitions of coronary artery variations, and clinical outcomes, quantitative pooling and meta-analysis were considered inappropriate. Therefore, the findings were synthesized descriptively. Categorical findings, including types of coronary dominance, origin anomalies, myocardial bridging, coronary fistulae, clinical manifestations, and risk-of-bias categories, were summarized using reported frequencies and patterns across the included studies. Sample sizes and other study characteristics were presented descriptively, and similarities and differences in anatomical and clinical findings were compared narratively. No pooled effect estimates, heterogeneity statistics, or inferential statistical tests were calculated because the review was designed as a qualitative systematic review. Results were presented in structured tables and accompanied by narrative synthesis to facilitate comparison across the included studies.

RESULTS

Total of 11 studies published between 2021 and 2025 were included in the qualitative synthesis. The studies represented populations from Asia, the Middle East, and Europe. Most studies employed retrospective, observational, cross-sectional, or cohort designs. Sample sizes ranged from 289 to 28,800 patients, demonstrating considerable heterogeneity in the sizes and characteristics of the study populations. CCTA was the

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most frequently used diagnostic modality, followed by conventional coronary angiography and CT (Table 1).

Table 1: Characteristics of Included Studies (2020–2025)

Sr. No.	References	Country	Study Design	Sample Size	Modality
1	[12]	Iran	Cross-sectional	742	CCTA
2	[13]	India	Retrospective single-centre cohort study	8,000 patients; 133 had coronary anomalies	Coronary angiography and CCTA
3	[14]	India	Cross-sectional	512	CCTA
4	[15]	Türkiye	Observational	405	CT
5	[16]	China	Cohort	289	CCTA
6	[17]	Saudi Arabia	Retrospective	1,098	CCTA
7	[18]	India	Retrospective single-centre observational study	28,800 patients; 1,186 with coronary artery anomalies	Conventional coronary angiography
8	[19]	United Kingdom	Observational	450	CT
9	[20]	Türkiye	Cross-sectional	650	CCTA
10	[21]	Nepal	Retrospective single-centre angiographic study	6,000 patients; 89 with coronary artery anomalies	Conventional coronary angiography
11	[22]	Europe	Diagnostic study	390	CCTA

Among studies that evaluated coronary dominance, right coronary dominance was the most frequently reported pattern, although dominance was not assessed by Vallurupalli and Hachathodi [13] or Bansal et al. [18]. Common origin anomalies included separate origins of the LAD and LCx and anomalous origin of the RCA from the left coronary sinus. Myocardial bridging was reported in several studies, whereas coronary artery fistulae were uncommon. Other variations included anomalous LCx origin, absent or short left main coronary artery, dual LAD, coronary ectasia, aneurysm, high-take-off coronary arteries, and retro-aortic courses. The distributions of these variations are summarized (Table 2).

Table 2: Coronary Artery Anatomical Variations Reported by the Included Studies

Sr. No.	References	Sample Size	Dominance Pattern	Common Origin Anomaly	Myocardial Bridging	Coronary Fistula	Other Reported Variations
1	[12]	742	Right dominant	RCA from left sinus	Present	Rare	Interarterial course variants
2	[13]	8,000	Not assessed	RCA from left sinus	Present	Rare	LCx from right sinus
3	[14]	512	Right dominant	Separate LAD and LCx origins	Frequent	Rare	Coronary ectasia variants
4	[15]	405	Right dominant	Anomalous RCA origin	Present	Rare	Coronary course anomalies
5	[16]	289	Right dominant	AAOCA variants	Present	Uncommon	Interarterial high-risk course
6	[17]	1,098	Right dominant	High-take-off origin	Frequent	Rare	Myocardial bridging
7	[18]	28,800	Not assessed	Separate LAD and LCx origins	Present	Rare	Coronary ectasia and aneurysm
8	[19]	450	Right dominant	Separate coronary ostia	Present	Rare	Coronary duplication
9	[20]	650	Right dominant	RCA from left sinus	Present	Rare	Retro-aortic course
10	[21]	6,000	Right dominant	RCA from left sinus	Not evaluated	Rare	Absent left main and dual LAD
11	[22]	390	Right dominant	Anomalous coronary origin	Present	Rare	CT-detected anatomical variants

The clinical implications of coronary artery variations depended principally on their origin and anatomical course. Myocardial bridging was commonly associated with exertional or atypical chest pain and possible reversible ischemia. Conversely, separate coronary ostia, coronary duplication, anomalous LCx origin, and several branching variations were generally benign or incidentally detected. Nevertheless, recognition of these variants remained important for coronary catheterization, percutaneous intervention, and cardiac surgery. The clinical significance of the reported variations is presented (Table 3).

Table 3: Clinical Implications of Coronary Artery Variations

Sr. No.	References	Coronary Variation	Clinical Presentation	Modality	Reported Clinical Significance
1	[12]	RCA from opposite sinus	Syncope or exertional chest pain	CCTA	Potential risk of myocardial ischemia
2	[13]	RCA from opposite sinus	Chest pain	Angiography and CCTA	High-risk courses may cause ischemia
3	[14]	Separate LAD and LCx origins	Usually, asymptomatic	CCTA	Generally, a benign anatomical variant
4	[15]	Coronary course anomaly	Chest pain	CT	May mimic coronary artery disease
5	[16]	Interarterial high-risk course	Syncope or risk of sudden cardiac death	CCTA	High-risk anomaly requiring assessment and follow-up
6	[17]	Myocardial bridging	Exertional angina	CCTA	Associated with reversible ischemia

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7	[18]	Myocardial bridging	Atypical chest pain	Angiography	May be associated with myocardial ischemia
8	[19]	Coronary duplication	Incidental finding	CT	Usually, no major clinical consequence
9	[20]	Retro-aortic course	Atypical angina	CCTA	Usually benign but may cause diagnostic difficulty
10	[21]	Anomalous RCA origin	Detected during angiography	Angiography	Important for interventional planning
11	[22]	Multiple coronary variants	Incidental findings	CCTA	Most variants were clinically insignificant

Assessment using the modified Newcastle-Ottawa Scale demonstrated generally acceptable methodological quality. Nine of the 11 studies were classified as having a low risk of bias, while two studies had a moderate risk of bias; no study was classified as having a high risk of bias. Low-risk studies generally had clearly defined populations, appropriate participant selection, and objective imaging-based evaluation of coronary anatomy. Moderate risk was mainly associated with limited control of confounding variables and methodological limitations of selected observational designs. The individual quality scores are presented (Table 4).

Table 4: Risk-of-Bias Assessment Using the Modified Newcastle-Ottawa Scale

Sr. No.	References	Selection (4)	Comparability (2)	Outcome (3)	Total Score	Risk of Bias
1	[12]	4	1	3	8	Low
2	[13]	3	1	3	7	Low
3	[14]	3	1	2	6	Moderate
4	[15]	3	1	2	6	Moderate
5	[16]	4	2	3	9	Low
6	[17]	4	1	3	8	Low
7	[18]	4	1	3	8	Low
8	[19]	3	1	3	7	Low
9	[20]	4	1	3	8	Low
10	[21]	4	1	3	8	Low
11	[22]	4	1	3	8	Low

AAOCA, anomalous aortic origin of a coronary artery; CAD, coronary artery disease; CT, computed tomography; LAD, left anterior descending artery; LCx, left circumflex artery; RCA, right coronary artery; UAE, United Arab Emirates

DISCUSSION

This systematic review demonstrates that coronary artery anatomy encompasses a broad spectrum of variations, ranging from common benign anatomical patterns to uncommon anomalies with potentially serious clinical consequences. Across the included studies, right coronary dominance was consistently the most frequently reported coronary dominance pattern. This observation is consistent with contemporary imaging literature showing that many coronary artery variations are asymptomatic and are detected incidentally during coronary computed tomography angiography (CCTA) [20]. Large population-based imaging studies have similarly demonstrated that true congenital coronary anomalies constitute only a small proportion of individuals undergoing coronary imaging, supporting the distinction between relatively common anatomical variants and comparatively uncommon clinically significant anomalies [20]. Furthermore, contemporary imaging evidence emphasizes the important role of CCTA in the non-invasive delineation of coronary artery origin, proximal course, and its relationship with surrounding cardiovascular structures [23]. Among the coronary course variations identified in this review, myocardial bridging was one of the most frequently reported findings. Previous systematic review and meta-analytic evidence have also demonstrated a substantial prevalence of myocardial bridging across imaging-based and cadaveric studies [24]. Additional contemporary literature describes myocardial bridging as an important coronary course variation characterized by an intramyocardial segment of an epicardial coronary artery that may undergo systolic compression [25]. Although myocardial bridging has historically been regarded as a largely benign anatomical finding, evidence suggests that selected patients may develop clinically important consequences, including reversible myocardial ischemia and myocardial infarction [26]. Associations with exertional angina and coronary artery disease have also been described, particularly among symptomatic patients [27]. Similarly, recent cohort-based evidence has reported myocardial bridging as a frequently identified coronary anomaly among individuals undergoing coronary angiographic assessment [28]. An anomalous origin of a coronary artery, particularly origin from the opposite aortic sinus with an interarterial course, represented the most clinically concerning abnormality identified in the present review. Contemporary clinical evidence indicates that anomalous aortic origin of a coronary artery may be associated with myocardial ischemia, ventricular arrhythmias, exertional syncope, and sudden cardiac death, particularly when the anomalous vessel follows a high-risk course between the great arteries [29-31]. Although such anomalies are relatively uncommon, their potentially severe consequences make accurate anatomical characterization clinically important [32]. Multimodality imaging, particularly CCTA, facilitates assessment of the coronary ostium, proximal vessel morphology, and relationship of the anomalous artery to the aorta and pulmonary artery, thereby helping differentiate lower-risk anatomical patterns from those that may require closer surveillance or intervention [23]. These observations are consistent with the findings of the present review, in which malignant interarterial courses

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were repeatedly identified as high-risk coronary abnormalities with important prognostic implications. In contrast, several other coronary artery variations identified in the included studies, including separate ostial origins of the left anterior descending and left circumflex arteries, coronary duplication, branching variations, and high take-off coronary arteries, were predominantly described as benign or incidental findings. Contemporary literature similarly indicates that many coronary anatomical variants have little or no direct functional consequence in otherwise asymptomatic individuals [20]. Some reports have additionally suggested associations between selected coronary abnormalities and coronary vasomotor disturbances or endothelial dysfunction in the absence of significant obstructive coronary disease [33-35]. Therefore, even anatomically benign variations may have procedural or diagnostic significance, emphasizing the importance of accurate pre-procedural identification and documentation. Taken together, the findings of this review indicate that the clinical importance of coronary artery variations is determined primarily by the origin, proximal course, anatomical relationships, and potential physiological consequences of the involved vessel rather than by the mere presence of an anatomical variation. Benign coronary patterns are relatively frequent and are commonly detected incidentally, whereas anomalous courses involving potentially compressive or ischemia-producing pathways carry greater prognostic significance. Advances in CCTA have substantially improved visualization and characterization of coronary anatomy, thereby supporting more accurate risk stratification and clinical decision-making [23]. Contemporary evidence further indicates that early and precise recognition of coronary abnormalities can help distinguish harmless anatomical variants from potentially life-threatening anomalies and can guide appropriate follow-up, intervention, or surgical planning [27]. These findings reinforce the importance of integrating detailed coronary anatomical assessment into both diagnostic evaluation and procedural planning.

Several limitations should be recognized in this systematic review. First, there was a significant inter-study variation in study design, population characteristics, sample size, diagnostic modality, and classification of coronary artery variations, making it impossible to make meaningful quantitative pooling or meta-analysis. Second, most of the studies that were included were observational or retrospective, and these types of studies can be subject to selection bias, as well as limiting the ability to determine causal relationships between anatomical variations and clinical outcomes. Furthermore, several of the studies included here were conducted on a small number of children or on a clinical population, which may affect the generalizability of the results. More studies, however, need to focus on large, prospective, multicenter studies with standardized definitions and imaging protocols for coronary artery anomalies in the future. Long-term follow-up studies are also needed to identify the natural history and prognosis of particular variants of the anatomy.

CONCLUSIONS

Anatomical variations of the coronary arteries are routinely detected using modern cardiac imaging techniques, but those with significant clinical impact are still relatively rare. The results of this systematic review suggest that the clinical and prognostic importance of a coronary variation is primarily related to its origin, anatomical course, and relation to neighboring cardiovascular structures and not to the mere existence of a variation. While most often they are harmless, some variants, like separate ostial origin and high take-off coronary artery, are important conditions during catheterization and cardiac surgery. Anomalous coronary arteries with an interarterial course and certain forms of myocardial bridging can, however, be the cause of myocardial ischemia or syncope, arrhythmia, or sudden cardiac death. CCTA is especially useful in the characterization and risk stratification of these abnormalities with accuracy. Proper diagnosis and classification of coronary artery variations is thus crucial to avoid misdiagnosis, to inform planning of interventional and surgical procedures, risk stratification, and personalized management.

Authors' Contribution

Conceptualization: IJ
Methodology: IJ, NQ, AS
Formal analysis: SI, SS
Writing and Drafting: AFQ
Review and Editing: AFQ, IJ, NQ, SI, AS, SS

All authors approved the final manuscript and take responsibility for the integrity of the work

Conflict of Interest

All the authors declare no conflict of interest.

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