# Interventional Cardiology Imaging

## An Essential Guide

Amr E. Abbas
*Editor*

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*This book is dedicated to my parents, El-Sayed and Raifa, who I owe everything to and then more, my wife, Mona, who I love dearly and lots, my children, Zane and Layla, who are my life and then some, and my co-authors, who without them, this book would not be possible.*

# Preface

Ever since the establishment of invasive coronary angiography, the limitations of the technique have not gone unnoticed. As a result, multiple invasive imaging modalities have been developed in an attempt to characterize the true severity of coronary artery disease as well as guide the percutaneous coronary interventions.

Invasive imaging modalities have included ultrasound, optical, and chemographic technologies. Moreover, physiological assessment of the degree of the coronary blood flow has also been performed through fractional and coronary flow assessments.

This book provides an overview of the current available invasive coronary imaging modalities in an attempt to present a concise review of their current technologies, indications, appropriate use, and pitfalls. It is an invaluable tool for interventional cardiologists and cardiologists in training who wish to have a concise and practical review of all these modalities.

Royal Oak, MI, USA Amr E. Abbas, MD, FACC, FSCAI, FSVM, FASE, RPVI

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# 1 Basic Coronary Artery Anatomy and Histology

Alfred C. Burris II and Mazen Shoukfeh

**Abstract**

An interest in coronary anatomy dates back to the sixteenth century when Renaissance scholars began anatomic investigation. This was preceded by philosophical and theological teachings of Greek and Arabic scholars such as Aristotle (384–322 BC) and Galen of Pargamum (129–199 AD). Prior to the twentieth century, anatomic analysis of the coronary arteries were based solely on gross anatomic inspection. With the advent of catheter based selective coronary angiography in 1962 by Mason Sones, there has been an increased awareness of variation in the "normal" coronary anatomy. This has been further clarified most recently by computed tomography angiography. A thorough understanding of normal coronary anatomy and variations are imperative in making accurate diagnoses and providing effective management.

**Keywords**

Coronary vascular anatomy • Coronary histology • Anatomic analysis of coronary arteries • Normal coronary anatomy • Myocardial bridging • Right coronary artery • Left main artery • Left anterior descending artery • Left circumflex artery

## Introduction

An interest in coronary anatomy dates back to the sixteenth century when Renaissance scholars began anatomic investigation. This was preceded by philosophical and theological teachings of Greek and Arabic scholars such as Aristotle (384–322 BC) and Galen of Pargamum (129–199 AD) [1]. Prior to the twentieth century, anatomic analysis of the coronary arteries were based

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solely on gross anatomic inspection. With the advent of catheter based selective coronary angiography in 1962 by Mason Sones, there has been an increased awareness of variation in the "normal" coronary anatomy [2]. This has been further clarified most recently by computed tomography angiography [3–5]. A thorough understanding of normal coronary anatomy and variations are imperative in making accurate diagnoses and providing effective management.

## Normal Coronary Anatomy

Coronary arteries are the only branches of the ascending aorta. Traditionally a coronary artery has been described as any artery or arterial branch that carries blood to the cardiac parenchyma [1]. The cardiac parenchyma is defined as any structure located in the pericardial cavity and includes not only the myocardium but also structures such as the pulmonary truck, the superior vena cava, and the semilunar valves. Coronary arteries are located on the epicardial surface of the heart. Septal perforators would be the exception and run intramuscularly in the ventricular septum. Coronary arteries are named based on the vessels' distal vascularization territory but not its origin [1]. This would explain the description of coronaries with anomalous origin: a right coronary artery that arises from the left coronary cusp remains a right coronary artery. The left anterior descending artery (LAD) is defined as the artery that runs within the interventricular septum, the right coronary artery is defined as the artery supplying the major blood supply to the right ventricle, and the circumflex is defined as the third major epicardial artery.

"Normal" coronary anatomy is that which occurs in greater than 99 % of the general population [6], and any variation is considered an anomaly. The true incidence of coronary anomalies has been reported from 0.3 % to 1.6 % by autopsy or cardiac catheterization, respectively and are discussed elsewhere [7]. However, gender differences have not been well described. Newer imaging modalities such as coronary CTA may be a better representation of the population; as it represents a more diverse patient population [3]. Angiographic studies, both invasive and noninvasive, have shown some common anatomical variation within the "normal" anatomy.

## Origin from the Sinus of Valsalva

The aortic root is the initial part of the ascending aorta that consists of three sinuses of Valsalva: right, left, and posterior. The posterior sinus is also referred to as the non-coronary sinus. Each sinus correlates with a leaflet of a tri-leaflet aortic valve. The right and left sinus of valsalva lie anteriorly, and are the site or origin for the right and left coronary arteries, and lie adjacent to the pulmonary root (Fig. 1.1). The aortic root begins at the aortic annulus and extends distally to the sinotubular junction; an area of circumferential thickening that divides the aortic root from the ascending aorta.

Coronary ostia typically arise from the middle of the right and left sinus of valsalva; below the sinotubular junction and above the free margin of the corresponding open aortic valve leaflet [1, 8]. This allows for maximal coronary filling during diastole. A coronary ostium that that arises above or below the sinus of valsalva is termed to be a variant of normal anatomy (Fig. 1.2). If the ostium of a coronary artery takes off >1 cm above the sinotubuluar junction, it is considered a high take off or ectopic position [9]. This has been described to be associated with decreased diastolic filling and chronic ischemia in the absence of epicardial stenosis [10].

Normally, there are two to three coronary ostia [11]. Two ostia are more common and correspond with the left and right coronary arteries. The third typically comes from a separate ostium for the conus or infundibular branch that is present in 23–51 % or normal hearts [1, 12] and has been referred to as the "third coronary artery". Less commonly, there is an absence of the left main with separate ostia of the left anterior descending and the left circumflex arteries (Fig. 1.3). The ostial orientation is generally orthogonal to the aortic root or ascending aorta [6]. Although there is some variation, the right coronary artery ostium generally arises in the vertical plane and the left coronary in the horizontal plane (Figs. 1.4, 1.5, and 1.6).

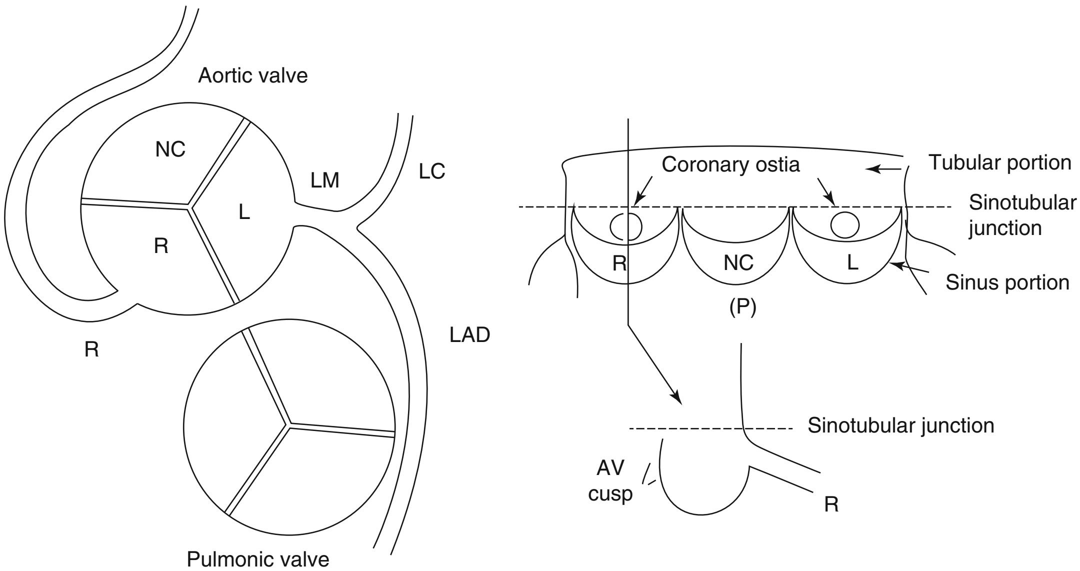


**Fig. 1.1** Figure displaying normal ostia of the left and right coronary arteries arising from the left and right coronary cusps, respectively. Notice the ostia arise between the margin of the aortic valve leaflets and sinotubular junction. The coronary arteries include: *R* right coronary, *L* left coronary, *LM* left main, *LAD* Left anterior descending. The aortic valve cusps: *R* right, *L* left, *NC* noncoronary (or posterior) (From Waller et al. [8] with permission)

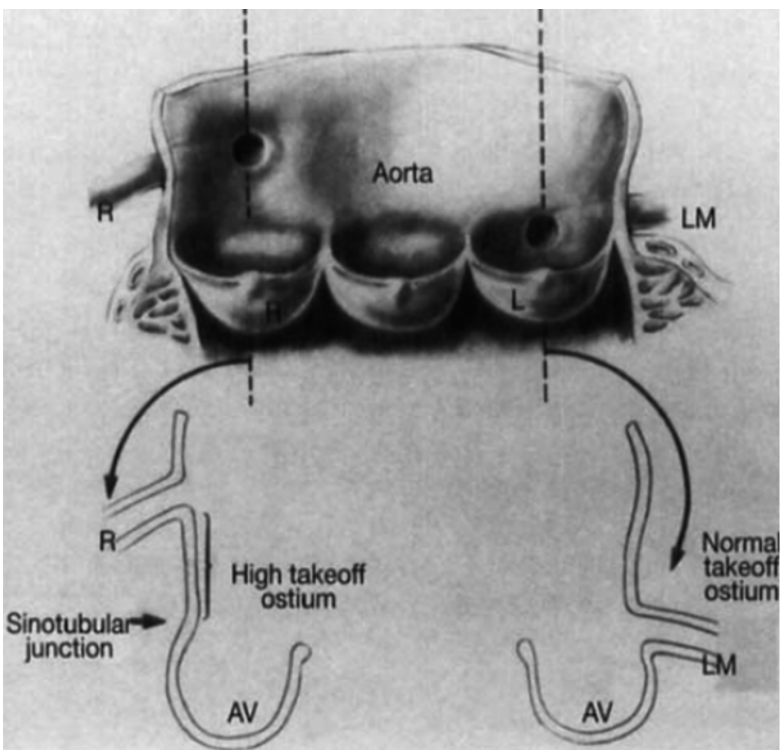


**Fig. 1.2** Figure displays the normal take off of the left main and high takeoff off of the right coronary artery. Each artery arises from the proper coronary cusp-the right and left coronary arteries arise from the right and left coronary cusps, respectively. *R* right, *L* left, *LM* left main, *AV* aortic valve (From Waller et al. [8] with permission)

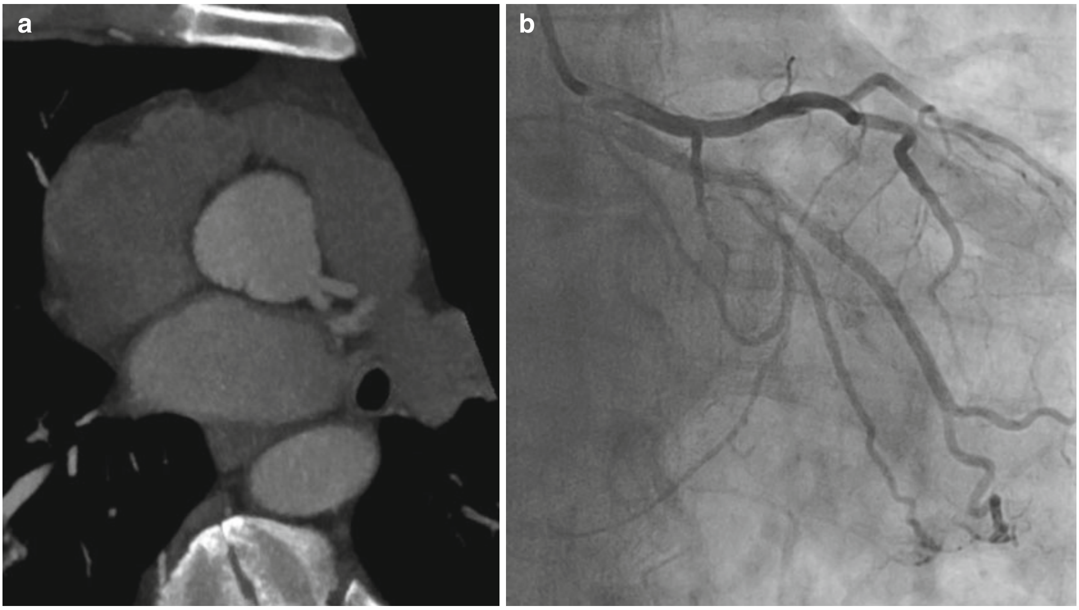


**Fig. 1.3** Figures demonstrate an absent left main with the left anterior descending and left circumflex arteries arising from separate ostia in the left sinus of valsalva (**a**) left coronary CTA and (**b**) right selective coronary angiography

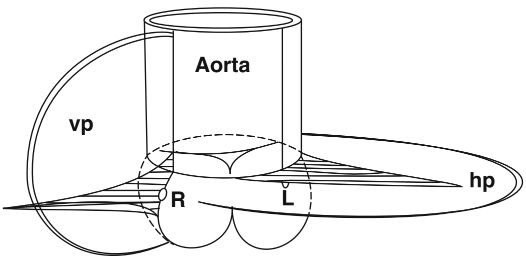


**Fig. 1.4** This figure represents the coronary orientation in regard to the aortic root and ascending aorta. The right and left coronary artery ostia are oriented in a vertical plane (*vp*) and horizontal plane (*hp*), respectively (From Angelini [6] with permission)

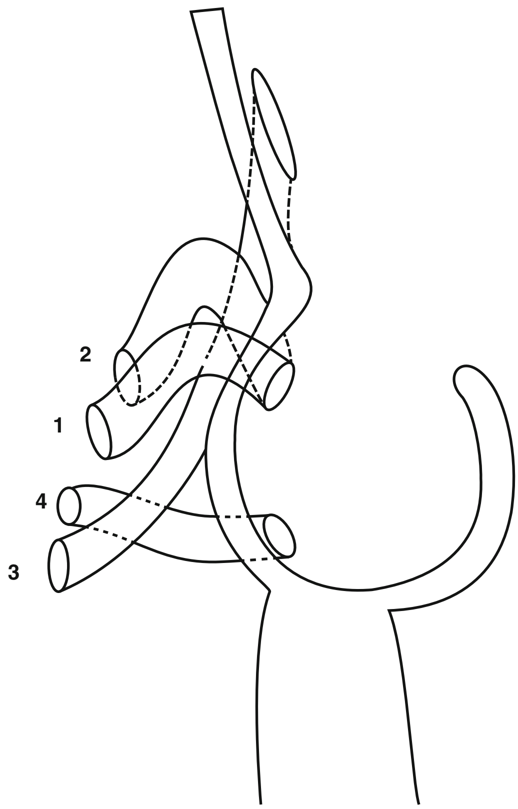


**Fig. 1.5** This represents a cross sectional view of the variable right coronary ostium orientation. (*1*) Normal and remains orthogonal to the aorta in the vertical plane (*2*) Upward takeoff (*3*) Downward takeoff (*4*) Horizontal orientation (From Angelini [6] with permission)

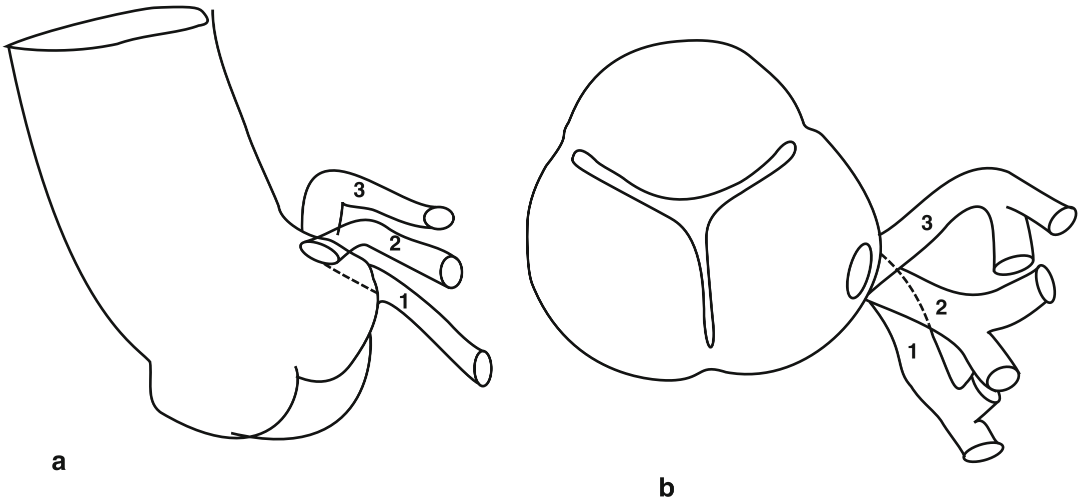


**Fig. 1.6** The orientation of the left coronary artery ostium in the frontal (**a**) and horizontal (**b**) planes. (*1*) Inferior tilt (*2*) Normal orthogonal orientation (*3*) Superior tilt (From Angelini [6] with permission)

## Myocardial Bridging

Normal epicardial coronary arteries occasionally take a short intramyocardial course. This causes arterial compression during systole referred to as milking or systolic "myocardial bridging". Although this can occur in any vessel, it is most commonly seen in the LAD. Myocaridal bridging is reported as frequently as 25 % by autopsy studies and 2 % angiographically [13–15]. Generally, myocardial bridging is considered a benign phenomenon, as the 5-year survival remains high with rare reports of sudden cardiac death. Despite the fact that much of the coronary compression occurs during systole and the majority of coronary perfusion occurs during diastole, there are reports of underlying ischemia driven by myocardial bridging [16, 17]. This has been described in patients with long segments of an intramyocardial course. Increased heart rates and decreased diastolic filling pressures contribute to ischemia by decreasing diastolic filling time and increased systolic coronary compression, respectively.

## The Coronary Arteries

### Right Coronary Artery

The right coronary artery (RCA) arises anteriorly from the right coronary cusp and travels anteriorly and posteriorly in the atrioventricular groove [18, 19] (Figs. 1.7 and 1.8). If the RCA is the dominant vessel, it travels posteriorly and provides branches along the interventricular groove and lateral wall of the left ventricle; the posterior descending artery and posterolateral branch, respectively.

The usual dominant RCA is 12–14 cm in length prior to giving off a PDA [20]. The luminal diameter generally ranges from 1.5 to 5.5 mm with a mean of 3.2 mm [20]. While the LAD and LCX tend to taper as they progress distally, the diameter of the RCA remains relatively constant until just prior to the take off of the PDA. The first branch of the RCA is the infundibular or conus branch in 50 % of the population. This supplies the right ventricular outflow tract and often anastomoses with an infundibular branch of the left anterior descending artery forming the circle

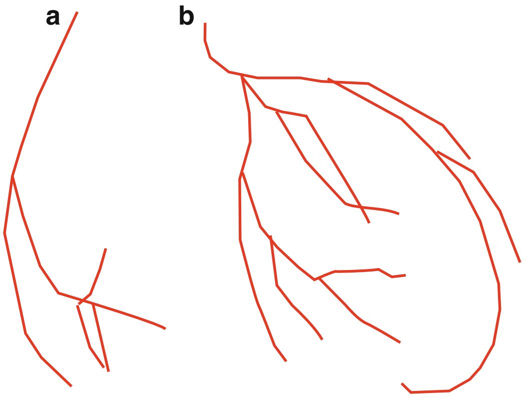


**Fig. 1.7** Wire model of coronaries (**a**) RCA in LAO projection; (**b**) the Left coronary system in the RAO projection

**Fig. 1.8** This figure demonstrates normal coronary anatomy. The left and right coronary arteries arise from the respective aortic cusps. The left anterior descending artery courses anteriorly between the left and right ventricles. The left circumflex and right coronary arteries travel in the left and right atrioventricular grooves, respectively. *LAD* left anterior descending, *RCA* right coronary artery

of Vieussens [21]. In the other half, the conus branch arises from a separate ostium in the right coronary sinus of Valsalva. In 60 % of the population, the second branch of the RCA is the sinus nodal artery [22]. In the remaining 40 %, the sinus nodal artery is a branch from the circumflex artery. The RCA then gives off small branches supplying the right atrium and ventricle. The largest of these is the acute marginal artery; which supplies much of right ventricular free wall [23]. If the RCA is dominant, it supplies two several major branches: (1) the posterior descending artery (2) posterolateral branch. The posterior descending artery travels in the posterior interventricular grove and supplies the posterior inferior septum. If the left anterior descending artery does not reach the apex of the heart, the PDA can supply the distal third of the interventricular septum. The posterolateral branch (es) supply the lateral wall. Just distal to the PDA, the RCA occasionally supplies an AV nodal branch [8].

## Left Main Artery

The left main (LM) artery originates from the left sinus of Valsalva and travels anteriorly and leftward (Figs. 1.7 and 1.8). It is positioned between the left atrial appendage and the pulmonary trunk [5]. This divides into two major branches: the left anterior descending (LAD) and left circumflex (LCX) arteries. The LM varies in length from 0.5 to 2.5 cm but remains uniform in caliber throughout its length [20, 24, 25]. The LM can trifurcate providing a third branch referred to as a ramus intermedius (RI) (Fig. 1.9). The RI originates between the LAD and the LCX and supplies the territory of the obtuse marginal and/or the diagonal [25]. The luminal diameter of the LM is usually 2.0–5.5 mm with a mean of 4 mm [20].

## Left Anterior Descending Artery

The LAD extends from the left main and curves around the pulmonary trunk prior to entering the anterior interventricular groove and extending to the apex [26]. The left anterior descending artery then extends distally to the apex within the inferior interventricular sulcus towards the crux of the heart. It then provides branches to the inferior walls of both ventricles [26]. The vessel terminates in the interventricular groove prior to the posterior (inferior) descending artery (Figs. 1.7 and 1.8). The anterior descending artery provides two major branches: septal perforator arteries and diagonal branches. The septal perforator arteries branch at right angles from the anterior descending artery and supply the anterior two thirds of the intraventricular septum [22]. The diagonal branches are typically larger than the septal perforators and supply the lateral wall of the left ventricle. The diagonal branches are sequentially numbered as they arise from the LAD. The anterior descending artery can also produce an infundibular/conal branch. The LAD is generally has a luminal area from 2.0 to 5.0 mm with an average of 3.6 mm [20].

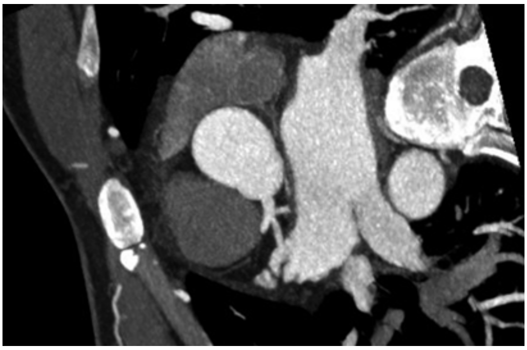

**Fig. 1.9** Ramus Intermedius. In some individuals, instead of the typical bifurcation into the LAD and LCX, the left main trifurcates into an LAD, LCX, and ramus intermedius (RI), the RI coursing between the LAD and LCX. This can be difficult at times to differentiate from a early diagonal branch of the LAD or obtuse marginal of the LCX

## Left Circumflex Artery

The left circumflex artery has a branching angle from the main stem that is variable. It then courses through the left atrioventricular groove [26]. This artery provides obtuse marginal branches that are sequentially numbered as they arise from the LCX and supply the posterior and lateral wall of the left ventricle (Figs. 1.7 and 1.8). If this is the dominant vessel, it provides the PDA and PLB; rather than the right coronary artery (Fig. 1.10). The luminal area of the LCX is generally 1.5–5.5 mm with an average of 3.2 mm [20].

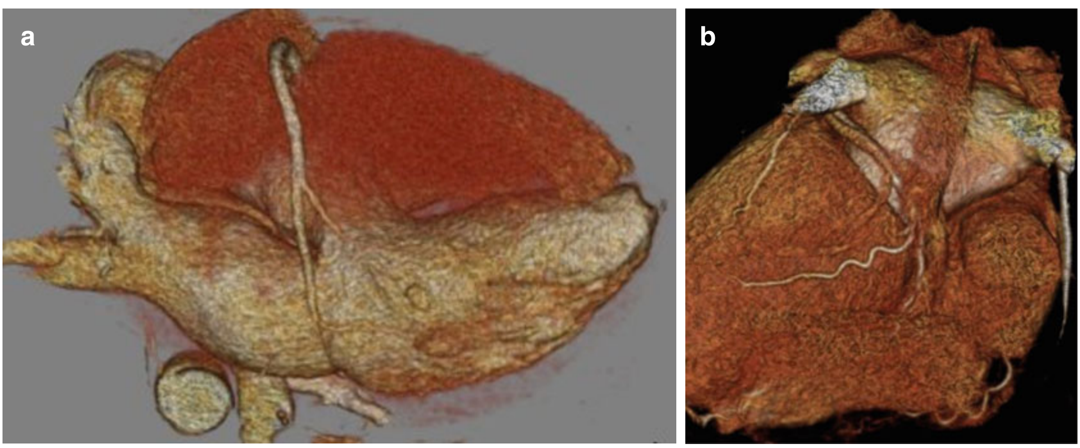


**Fig. 1.10** Coronary Dominance. Coronary dominance is determined by the vessel that supplies the posterior descending (PDA) and posterolateral branches (PLB) to the inferior wall of the left ventricle. The right coronary artery is considered dominant if it supplies both the PDA and PLB as seen in (**a**). The left circumflex is considered dominant if it supplies both as seen in (**b**). It is considered a co-dominant system if the RCA supplies the PDA and the LCX supplies the PLB

## Dominance

The vessel that supplies the PDA and PLB determines coronary dominance (Fig. 1.10). The artery that supplies both vessels is considered the dominant vessel. If one provides the PDA and the other provides the PLB, it is considered to be ***co-dominant*** or have balanced dominance. In the general population, dominance of the right coronary artery is most common and has been described in up to 89 % of the population. The left coronary artery is dominant in approximately 7–8 % of the population [27–30]. A co-dominant system was noted in approximately 4 % of the population. The clinical significance of dominance is not entirely clear, though there have been data suggesting increased adverse events (cardiovascular related mortality and non-fatal MI) with those who are left dominant [30]. Some data suggest increased incidence of perfusion defects on nuclear studies.

## Segmental Anatomy

Segmental anatomy of coronary arteries is have been developed by the American Heart Association [31, 32] and is used for both research and anatomy reporting The coronary arteries are divided into proximal, mid, and distal segments.

RCA:
- Proximal-Segment from ostium to the acute marginal branch
- Mid-Segment that curves around the acute margin
- Distal-Posterior atrioventricular groove

LAD:
- Proximal-Segment from the ostium of the LAD to either the first septal perforator of the first diagonal branch
- Mid-Segment from the proximal segment to the second diagonal branch
- Distal-Segment from the mid segment to the terminal vessel

LCX:
- Proximal-Segment from the ostium to the first OM
- Distal-Segment distal to the first OM

## Histology

### Vessel Wall

The normal vessel wall is described as a trilaminar structure. The three layers include: tunica intima or interna, tunica media, and tunica adventitia (Fig. 1.11). Understanding the histological structure of the coronary arteries is essential in selecting and identifying the structures in the various coronary imaging modalities.

### Tunic Intima

The intima is the innermost layer of the normal arterial wall. The intima consists of three layers: (1) a lining layer of endothelial cells (2) a subendothelial layer of connective tissue with smooth muscle cells (3) a fenestrated internal elastic lamina (Figs. 1.11 and 1.12).

Arterial endothelial cells play a critical role in vascular homeostasis. Although previously believed to predominately play a passive barrier role, it is now recognized as playing a critical role in vascular tone, vascular permeability, balancing thrombosis and thrombolysis, inflammation/local immune response, and angiogenesis [33–36]. Disruption of these processes lead to vascular pathology ranging from atherosclerosis to thrombosis and aneurysmal dilatation.

The ***endothelium*** is a single layer of cells that serves as a semipermeable barrier between the blood plasma and interstitial tissue fluid. These cells are squamous, polygonal, and elongated with the long axis and direction of blood flow [8]. Endothelial cells are connected through occluding and gap junctions that, along with its

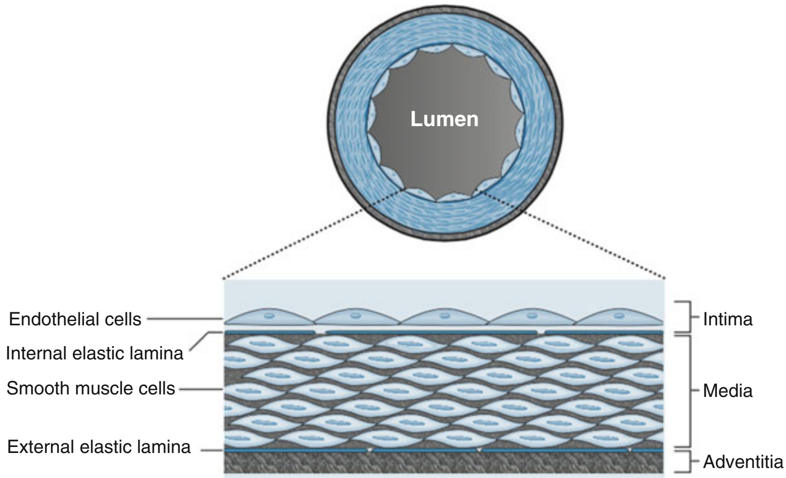


**Fig. 1.11** Arterial vessel wall: The arterial wall consists of three major layers: tunica intima, tunica media, and tunica adventitia. The tunic intima has an endothelial layer, connective tissue with a basement membrane, and an internal elastic membrane. The tunica media consists of elastic lamellae and smooth muscle cells. The inner and outer boarders are the internal and external elastic membranes, respectively. The tunica adventitia contains connective tissue and vasa vasorum

basal lamina, helps to regulate bidirectional exchange of molecules by processes such as, simple and active diffusion, receptor-mediated endocytosis, and transcytosis [33]. Vascular tone is regulated through the conversion of angiotensin I to angiotensin II and the production of vasoactive agents such as nitrous oxide and endothelins. It also allows for blood to remain in a liquid state by expression of heparin sulfate proteoglycan molecules. Contained within endothelial cells is thrombomodulin, which binds thrombin. If needed, the endothelium can also produce tissue and urokinase-type plasminogen activators with catalyze the activation of plasminogen to plasmin for fibrinolysis. Vascular endothelial growth factor (VEGF) also helps to maintain vasculature during tissue repair, growth, and regeneration. Vascular endothelium plays a vital role in inflammation and the local immune response through the migration of inflammatory cells to the site of injury.

The next layer within the tunica intima is the ***subendothelial space***. At birth, this contains nonfibrillar collagen (type IV collagen), laminin, fibronectin, and other extracellular matrix molecules [34–38]. This subintimal supporting tissue contains fibroblasts and other cells with structural features similar to smooth muscle cells known as myointimal cells. With age, arteries develop a thicker, more complex intima containing smooth muscle cells and fibrillar forms of interstitial collagen (type I and II). This more complex intima is often referred to by pathologists as diffuse intimal thickening, which does not necessarily correlate with lipid accumulation. It is currently unclear if this diffuse thickening reflects atherosclerotic burden. The intimal thickening is not uniform across the entire vascular bed. Atherosclerosis is a disease of the intima and is thought to be secondary to an increase in lipid accumulation of the myointimal cells.

The intima is separated from the media by an ***internal elastic membrane*** referred to as the basal lamina [34–36]. This is described as a fenestrated structure composed of elastin. With

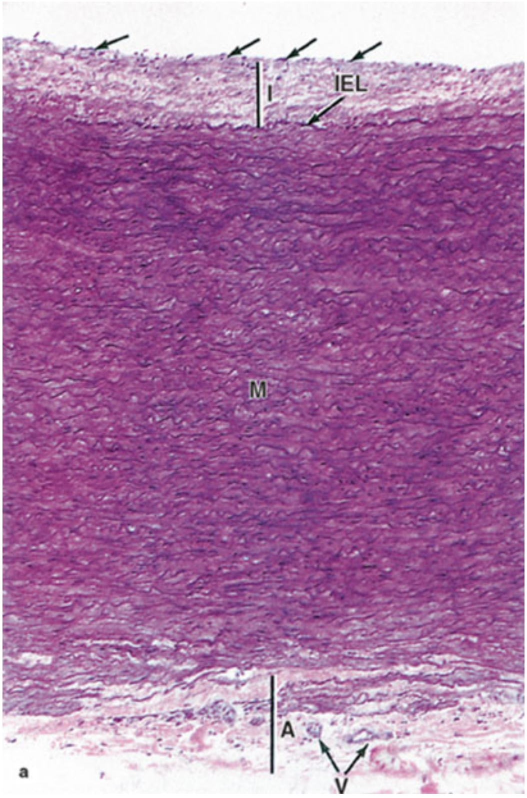


**Fig. 1.12** Tunics of the vascular wall: This represents the layers of the aorta. The *arrows* represent the simple squamous epithelium and the intima (*I*). This is separated from the media (*M*) by loose connective tissue and the internal elastic lamina (*IEL*). The media (*M*) contains elastic lamellae and elastic fibers alternating with layers of smooth muscle. Elastic fibers are also present in the adventitia (*A*). The vasa vasorum (*V*) are seen in the adventitia (From Mescher [33] with permission)

aging or intimal disease, this can be fragmented, duplicated, or focally lost [8]. Disruption of the internal elastic membrane can also represent previous angioplasty.

## Tunica Media

The media is the middle layer that serves mainly as the muscular layer of vessel wall. It consists of multiple helically arranged layers of smooth muscle cells and connective tissue. The internal and external borders of the tunica media are ***the internal and external elastic lamina*** (Figs. 1.11 and 1.12). The composition of the media differs depending on the location and size of the vessel. Depending on the characteristics of the media, arteries are classified as elastic or muscular.

**Elastic arteries** such as the aorta and pulmonary artery are describes as those that receive blood from the heart. The main branches such as aortic arch vessels and iliac arteries are included. These vessels are often greater than 10 mm in diameter and have a media containing a high density of elastic lamellar that are interspersed with smooth muscle. It has been describes as both contributing to the arterial structural integrity and storage of the kinetic energy produced by left ventricular contraction. This is imperative in maintaining forward flow of blood during diastole. The adult aorta contains approximately 50 elastic lamellae; this is higher in patients with hypertension [34]. The highly pulsatile blood flow through elastic arteries decreases with age causing the increased peripheral resistance and higher systolic blood pressure. Because of the dense elastic lamellae, the internal elastic lamina is not easily visualized.

**Muscular arteries** such as the epicardial coronary arteries are typically those that perfuse end organs and generally measuring between 1 and 10 mm. These vessels have a media that is composed of less elastic lamellae and more smooth muscle [39, 40]. The media contains up to 40 layers of large smooth muscle cells interspersed in a variable amount of elastic lamellae. This allows for vasodilatation and constriction to maintain steady perfusion.

Normal medial thickness averages 200 μm with a range of 125–350 μm [41]. In the setting of underlying disease of the intima, the medial thickness decreases to 16–190 μm with a mean of 80 μm [41]. Of note, in normal arteries smooth muscle cells rarely proliferate. The extracellular matrix remains homeostatic. The media is separated from the adventitia by an external elastic membrane.

## Tunica Adventitia

The adventitial layer consists of fibrous tissue, principally type I collagen and elastic fibers, that is surrounded by vasa vasorum, nerves, and lymphatic vessels [8, 34, 37] (Figs. 1.11 and 1.12). The vasa vasorum is referred to as the "vessels of the vessel" and provides metabolites to cells of those layers. Although the lumen can provide oxygen and nutrients to the intima, larger vessels are too thick to be perfused by diffusion from the lumen. Unmyelinated sympathetic nerve fibers that penetrate the adventitia are referred to as vasomotor nerves and regulate vascular tone through neurotransmitters such as norepinephrine. Because neuronal fibers to not penetrate the media, neurotransmitters must diffuse through gap junctions to reach the smooth muscle cells of the media. The adventitia contains collagen fibrils in a looser array than the intima. Although the adventitia contains fibroblasts and mast cells, there are less cellular components to the adventitia than the media or the intima. The thickness of the adventitia ranges from 300 to 500 μm. Though it has yet to be proven in humans, there is evidence in animal models that mast cells contribute to aneurysm and atheroma [42].

### Conclusions

The normal coronary anatomy and histology described above, serves as a milieu through which coronary blood flow can occur and supply the myocardium. Through atherosclerotic changes, alteration of the coronary histology and less commonly anatomy can occur and is readily assessed and visualized by coronary artery imaging modalities. The following chapters will review the current available technologies for imaging of the coronary artery.

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