CHAPTER 4

Normal and Anomalous Coronary Arteries in Humans

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Part I

HISTORICAL BACKGROUND

Interest in coronary anatomy and the nature of the coronary vessels was cautiously aroused in the 16th century, when inquisitive Renaissance scholars began to perform anatomic investigations in the early European medical schools. Until then, anatomic knowledge had been heavily influenced by the philosophical and theological teachings of the ancient, rediscovered masters of the Greek and Arabic schools. Aristotle (384–322 BC), the philosophical interpreter of nature, and Galen of Pergamum (129–199 AD), the great physician, were the main authorities whose theories continued to dominate the medical schools of Salerno, Bologna, Padua, and eventually Louvain, Paris, and London during the Renaissance.

Leonardo da Vinci (1452–1519), a lone, ingenious spirit, examined a few animal hearts (probably of oxen) and also briefly touched on coronary anatomy while exploring the arcane viscera of the chest.[531] His main interest seemed to be in applying the principles of hydraulic physics to cardiovascular function. Leonardo tended to rely on instinctive curiosity rather than organized, formal methods. He left us only brief notes, accompanied by precise, faithful sketches of the coronary anatomy, including the aortic trifoliate valve, the right and left coronary ostia, and the proximal course of the right and left coronary arteries (Fig. 4.1). He noted that the coronary arteries become progressively smaller as they progress toward the cardiac apex.[531] He also accurately described the coronary veins and the coronary sinus; his observation of the arrangement of these structures supported his assumption that an artery is always accompanied by a vein.[531] Leonardo's approach exemplified the new method of critical, direct observation, which a little more than a century later would allow better-trained, more-disciplined scientists to understand how the circulation works.[531]

The presence of a pulmonary circulation organized in series with the systemic circulation had been postulated by isolated early researchers: Ibn-na-Nafis, a 13th-century Arab physician working in Damascus; Miguel Serveto, a passionate 16th-century Spanish theologian; and Cesalpino, a 16th-century anatomist from Padua, who coined the term "pulmonary circulation."[526] Nevertheless, it was not until 1628 that William Harvey (1578–1657), a physician trained in Padua but later active in London, and Cambridge, propounded a clear, complete, organized concept of the circulation, thereby founding the discipline of physiologic anatomy. Discovery of the systemic capillary network awaited the introduction of the microscope. It was Marcello Malpighi (1628–1694), operating mainly in Bologna, who first described the circulation of blood through the peripheral capillary network.[526]

Regarding the coronary arteries in particular, the founder of descriptive anatomy, the great Flemish anatomist Andreas Vesalius (1514–1564), produced a series of fundamental *tabulae anatomicae* (Venice, 1538), that were followed by his comprehensive treatise "De Humani Corporis Fabrica Libri Septem" (Basel, 1543), which became the basic textbook of anatomy for generations of physicians throughout Europe. Interestingly, one famous *tabula anatomica* showed the right coronary artery (RCA) originating from the left coronary artery (LCA) and coursing anterior to the pulmonary outflow tract (Fig. 4.2). Similarly, a single coronary ostium was mentioned by Fallopius (Venice, 1562).[508] Not until 1761, did G. P. Morgagni accurately and definitively describe the two main coronary vessels.[508] During the ensuing centuries, various investigators published occasional descriptions of peculiar or unusual coronary anatomic features: the work of A. C. Thebesius and R. Vieussens was especially noteworthy.[508]

With the advent of the 20th century, physicians became increasingly aware of the complexity and variability of the coronary anatomy. In 1926, this concept was reinforced and put into a biologic prospective by Grant and Regnier,[146] who
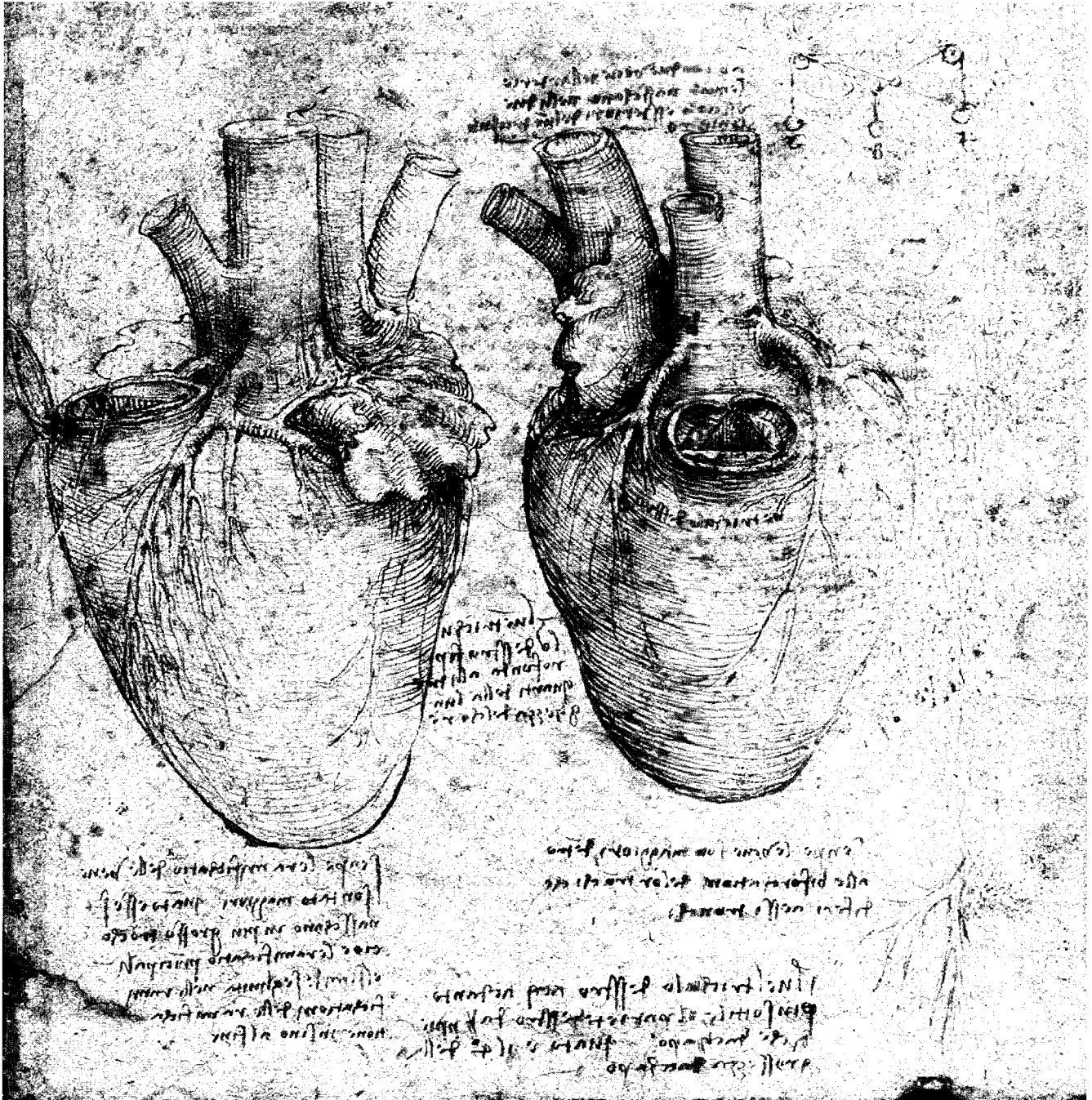
FIGURE 4.1. Leonardo da Vinci's drawings of the heart after removal of the pulmonary trunk above the valve (left drawing: lateral view; right drawing: frontal view). The two coronary arteries are clearly represented, one coursing on each side of the pulmonary outflow tract. The pulmonary sinuses are also precisely and correctly drawn in relation to the aortopulmonary contact point. (Courtesy of The Royal Collection©, Her Majesty Queen Elizabeth II.)
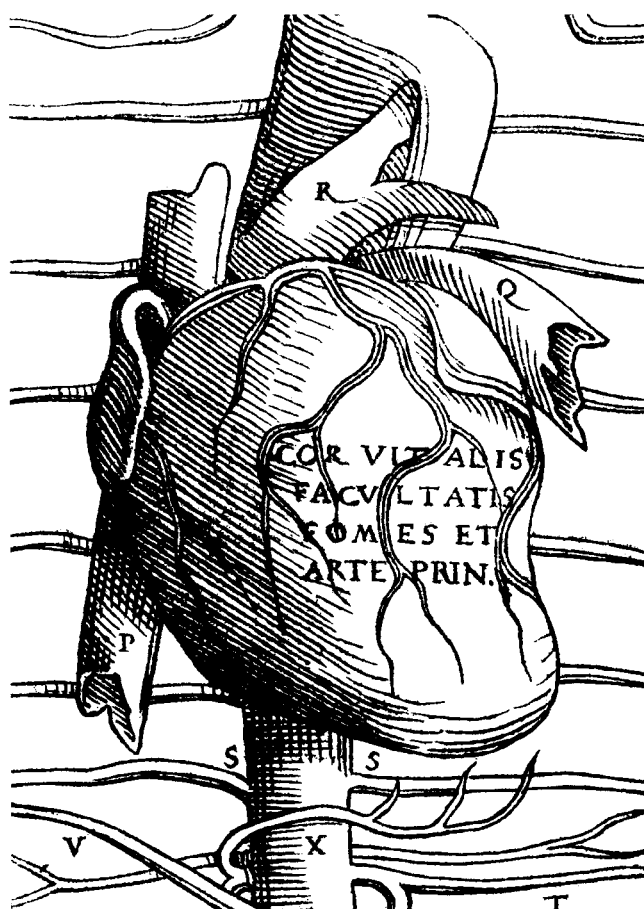
FIGURE 4.2. The coronary vessels (detail), as drawn in the "Six Tables" of Vesalius and Kalkar, from which Vesalius taught during his early years as professor of anatomy in Padua (see text). (Literary source, Vesalius A, Kalkar JS [1538]. Tabulae Anatomica, P.D. Bernard, Venice. Photo courtesy of the Blocker History of Medicine Collections, Moody Medical Library, The University of Texas Medical Branch, Galveston, TX.)

described the comparative anatomy of the coronary vessels in the different animal species. During the middle decades of the 20th century, several anatomists and surgeons made valuable contributions to the descriptive anatomy of the coronary arteries in humans. Particularly notable contributions were made by M. J. Schlesinger, J. E. Edwards, G. Baroldi, T. N. James, and W. C. Roberts.

The explosive popularization of selective angiography, as introduced by Mason Sones[370] in 1962, made cardiac specialists highly aware of the great variability of the coronary anatomy, even in the normal heart. Since then, thousands of short series and individual cases of coronary anomalies have been reported in the literature, eliciting not only widespread interest but also great frustration because of the complexity of the subject matter.

In 1967, Baroldi and Scomazzoni presented an excellent monograph summarizing the current knowledge of normal coronary anatomy.[508] During the 1960s, other investigators at the Armed Forces Institute of Pathology, in Washington

DC, undertook the pioneering project of describing congenital coronary anomalies in a coordinated, conceptual form.[42] Because their approach was based on clinical significance, they proposed to use the terms "minor and major" as organizing parameters in referring to coronary anomalies.[42] They further noted that some anomalies (such as seen in pulmonary atresia with intact ventricular septum and aortic atresia) were secondary consequences of congenital heart defects. This classification system became popular with several later authors, who simply added data from individual centers or unusual new cases to the same nosologic scheme. Another style that the Armed Forces group inaugurated (or indulged in) was to elaborate an embryogenetic theory based on anatomic observations of coronary anomalies. This theory assumed that the early embryonic coronary arteries were already present in the common undivided truncus, before any subdivision occurred, and that abnormal spiral septation of the truncus would cause ectopic origination.[42] Today we know that both assumptions (coronary origination from the undivided truncus and abnormal spiral subdivision of the truncus in cases of coronary anomalies) are erroneous, but the basic intuition that congenital anomalies have an embryogenic relevance was essentially correct and important. Unfortunately, as later authors came to realize, a morphogenetic explanation may not be so conveniently available in the absence of basic facts of normal descriptive embryology.[28]

An alternative classification device was introduced by Ogden,[285,286] who proposed to organize coronary anomalies according to anatomic morphologic parameters: anomalies of origin, course, and termination. Obviously, this approach was more comprehensive and rational than a system based only on clinical relevance, which depended on the evolution of medical opinion and practice.

Major contributions to the nosologic interpretation of coronary anomalies came from the most experienced centers and the most active pathologists, including J. E. Edwards, William C. Roberts, S. Bahrati, H. N. Neufeld, R. Virmani, and Hugh A. McAllister, Jr. More recent progress in the field of coronary artery interpretation has resulted from a more pointed approach aimed at (1) identifying the clinical relevance of certain apparently innocent morphologic variants by studying large populations, especially young persons dying suddenly of unclear causes, and (2) objectively documenting the claim of myocardial ischemia, especially by means of nuclear myocardial perfusion studies and provocation tests in the catheterization laboratory.

CORONARY ARTERY ANATOMY: WHAT IS NORMAL?

The only branches of the ascending aorta are the coronary arteries. They supply the heart and are two in number, right and left, arising near the commencement of the aorta immediately above the free margin of the semilunar valves. . . . The right coronary artery runs along its posterior surface as far as the posterior interventricular groove, where it divides

into two branches, one of which (transverse) continues on-ward in the groove between the left auricle and ventricle. . . . The other (descending) courses along the posterior interventricular furrow. *(Gray's Anatomy,* 1901 edition[509])

Since the beginning of this century, when the preceding passage was published in a leading textbook of human anatomy, there has been a continuously expanding awareness of the great variability of the coronary anatomy and the difficulty of defining normal coronary arteries. This expanding awareness has mainly been the result of the introduction of selective coronary angiography, coronary bypass surgery, and catheter-based angioplasty. A growing number of coronary features have become clinically relevant, and an increasing number of variants have become apparent. Today, discussions of this subject are far more detailed than would have been considered relevant just a few decades ago. Moreover, as further developments occur, discussions can be expected to become even more complex in the future.

So far, the rich literature on coronary anomalies has been marred by a recurrent, inconclusive debate about the definition of coronary normality: What is normal (or unusual but normal) as opposed to atypical, abnormal, aberrant,[234,235,505] anomalous, accessory, ectopic, incidental,[19] a variant,[414] or a less common variant? What is a major or minor[42,115] anomaly or a clinically[29,412] or hemodynamically[20,97,231] significant anomaly? At a time when confusion still governs the terminology and concepts related to coronary anomalies, we would like to propose a method of study and a discipline that may promote a more rational organization of the subject matter. In this method, *coronary anomalies are defined by exclusion, on the basis of a description of the normal coronary anatomic features.* This fundamental organizational concept, which one of us (PA) proposed in 1989,[480] seems to have been widely validated since that time.[82,105,302] Only by means of a feature-by-feature description of the normal coronary anatomy can coronary anomalies be defined. Some features, such as the presence or absence of a common main trunk of the left coronary artery (LCA), are dichotomous; in these cases, normal is easily defined ("normal is to have a common trunk"). Other features are better described on the basis of a continuous spectrum of quantitative data, which can be assessed with a normal, or Gaussian, distribution curve observed in large populations. In such cases, *"normal" should probably be defined as the interval between two standard deviations from the mean value,* as commonly used in biologic studies. Additionally, the terminology used to distinguish normal and abnormal coronary arteries should be based solely on morphologic grounds and should avoid the issue of clinical relevance. Clinical or functional repercussions of coronary anomalies are obviously important, and they will be discussed at the end of this chapter (see Pathophysiologic Mechanisms and Clinical Implications of Coronary Anomalies). Unfortunately, some questions cannot yet be resolved on the basis of currently available knowledge; in these cases, one can only propose certain criteria to be tested in further studies or certain empir-

ical solutions to be temporarily adopted by common agreement.

METHODS FOR STUDYING CORONARY MORPHOLOGY

Traditional descriptions of coronary morphology are based on anatomic observations in necropsy specimens. The primary tools are gross inspection and fine dissection with the aid of magnifying loupes. Injection/corrosion methods involve both injection of a semisolid gelatin mass or of chemical fibers (which tend to solidify in response to changes in temperature) and corrosion induced by changes in the chemical environment. Injection of radiopaque media, followed by radiography, is also a well-established method for evaluating autopsy specimens. Each of these observational methodologies has its indications, advantages, and limitations.

Gross Anatomic Inspection

Gross anatomic inspection—obviously the simplest, most readily available method for examining autopsy specimens—is often quite adequate. It is preferred for studying the coronary ostial anatomy, because it is well suited for describing the location of the ostia with respect to aortic root reference structures (the semilunar leaflets, commissures, and sinotubular junction). Gross anatomic inspection (sometimes with the aid of magnifying lenses) is also preferred for describing the intrinsic anatomic features of the proximal coronary anatomy (for example, slitlike ostial ridges in coronary arteries that originate tangentially with respect to the aortic wall). For evaluating a coronary artery's course, distal distribution, and termination (as in cases of small anomalous fistulous communications), the gross anatomic approach is less appropriate: it is not as precise as injection-corrosion or radiographic methods.

The great value of gross anatomic inspection lies in its convenience and negligible cost. Its most obvious limitation is its reliance on necropsy material. Indeed, because of the widespread clinical introduction of precise diagnostic imaging methods (such as computerized axial tomography, nuclear magnetic imaging, echocardiography, and angiography), necropsy studies are currently performed with decreased frequency.

Injection-Corrosion Techniques

Injection-corrosion techniques are quite satisfactory for showing coronary distribution patterns.[192,351,508] At their most sophisticated level of execution, these techniques can allow visualization of even the finest collateral network. However, because this approach depends on corrosion techniques to better delineate the coronary luminal spaces, it is inadequate for determining the relationship between coronary arteries and their adjacent structures (such as the depen-

dent myocardial segments). Moreover, injection-corrosion techniques are delicate, time-consuming, and expensive, requiring special technical knowledge on the part of the investigator. In recent decades, these techniques have largely been replaced by radiologic methods.

Radiologic Visualization

Radiology may be performed in vivo, as well as in cadaveric specimens. In recent decades, in vivo selective coronary angiography has become an unparalleled tool for studying coronary anatomy.[2,48,122,186,355,370,442] Because of this method's safety, its capacity for precise stereoscopic imaging (achieved by combining multiple simultaneous or sequential projections), and its excellent rendition of coronary anatomic details in motion (by means of enhanced radiologic techniques, digital enhancement, and electronic magnification), it is currently used in some 2 million patients per year worldwide. Moreover, it has been used in the great majority of recent investigational studies of coronary anatomy.

In cadavers, radiologic single-plane coronary angiography introduces a serious artifact, related to superimposition of the different planes (the cardiac free walls, septa, atria, and ventricles). This artifact tends to negate the advantage of greater detail during visualization of the fine coronary anatomy in a nonbeating heart. To overcome this technical problem, Schlesinger[351] proposed an ''unrolling technique'' by which the ventricular septum and both atrial walls are eliminated, transforming the cadaver heart into a flat surface. Obviously, this technique introduces other artifacts and precludes examination of certain relevant cardiac structures. Nevertheless, it is an expedient means of studying, for example, coronary dominance.

Newer Imaging Techniques

Because of its high cost, coronary angiography is not appropriate as a primary screening test for ruling out coronary anomalies. For this purpose, noninvasive clinical imaging techniques are safer, more convenient for the patient, and more cost-efficient—particularly echocardiography[6,123,131,] [331] but also nuclear magnetic resonance imaging[99,107,222,412,] [460,462,463] and computerized axial tomography at rapid rates of image acquisition. These methods can document the presence of a coronary anomaly or at least greatly raise the level of suspicion. For providing a thorough anatomic description, however, they are inferior to coronary angiography, not only because of their intrinsic physical characteristics but also because their basic approach is tomographic (whereas the coronary arteries do not lie in a single plane). Doppler signal interrogation can greatly enhance ultrasonographic imaging by facilitating vessel identification and providing flow velocity data. Echocardiography, magnetic resonance imaging, and computerized axial tomography can frequently allow diagnosis of the larger coronary fistulas and anomalous origination of a coronary artery from the pulmonary artery. Orig-

ination of a coronary artery from an anomalous aortic location or from the anomalous course of a proximal coronary artery can also be reliably identified with echocardiography,[456] especially using the transesophageal approach.[449,] [482] On the contrary, the distal coronary anatomy cannot be adequately visualized with these methods.[519,521]

Questions related to myocardial perfusion, especially those aimed at ruling out myocardial ischemia in the presence of coronary anomalies, can best be resolved by nuclear myocardial perfusion scintigraphy coupled with exercise or pharmacologic stress testing or by metabolic radioactive tracers coupled with positron emission tomography. In the near future, these testing modalities will become more relevant: they will be used to definitively and categorically establish the clinical relevance of certain coronary anomalies that are still unclear and to guide the management of individual patients, based on objective evidence of reversible segmental ischemia.

NORMAL CORONARY ARTERIES IN HUMANS: DESCRIPTIONS AND DEFINITIONS

A coronary artery is defined as any artery or arterial branch that carries blood to cardiac parenchyma (i.e., any structure located within the pericardial cavity). The cardiac parenchyma includes not only the myocardium but also the semilunar and atrioventricular valves, the great vessels (the proximal aorta, the pulmonary trunk, and a short segment of the superior vena cava), and the visceral pericardium or epicardium. The parietal pericardium should not be included, so the pericardial arteries should not be considered coronary.

The name and nature of a coronary artery or branch is defined by that vessel's distal vascularization territory, not by its origin. A coronary artery that arises from the right anterior sinus of Valsalva and that branches into the left anterior descending (LAD) and circumflex territories is not a right coronary artery (RCA) but, rather, a left main trunk with an ectopic origin. Similarly, *the different sinuses of Valsalva are identified not by the coronary arteries that originate from them but, rather, by their own topographic location.*

When considering the spectrum of coronary morphologies, *''normal''* should mean *''what is commonly observed,''* [394,480] and the terms *abnormal or anomalous* should be used for any form *observed in less than 1% of the general human population.*[480] This criterion is proposed as the dividing line between (1) normality, which would include the more frequent variations *(normal variants),* and (2) abnormality, which would consist of relatively infrequent variations *(anomalies).*

In essence, a useful convention is all that, on purely anatomic grounds, distinguishes a normal coronary artery pattern from an abnormal variant. Only certain anomalies (such as a coronary aneurysm) predispose the patient to a morbid state, and very few anomalies (such as anomalous origination of a coronary artery from the pulmonary artery) consti-

tute, in themselves, a disease state. Pathophysiologic and clinical considerations should be clearly distinguished from, and subordinate to, anatomic description.

With respect to its basic reference framework, the coronary artery anatomy should be related to the aortic sinuses at one extreme and the dependent myocardium at the other. The essential reference for describing the origination of the coronary arteries is the aortic root. *Anatomically, the aortic root consists of three equal-sized[507] semilunar leaflets, three intercuspal spaces,* and *three sinuses of Valsalva,* as well as *the sinotubular junction,* which separates the aortic root from the ascending aorta (Fig. 4.3). In a normal human heart, the aortic valve is situated posterior to—and slightly to the right

of—the pulmonary valve, just anterior to the recess between the tricuspid and mitral annuli (Fig. 4.4). The posterior wall of the aortic root is the anterior wall of the sinus transversus pericardii, a liquid-filled pericardial space that separates the aorta from the right and left atria (Fig. 4.4).

The aortic and pulmonary valves have a single adjacent contact point, which is the consistent remnant of the embryologic aortopulmonary septum (Fig. 4.4). This point is a useful reference for describing the semilunar cusps and sinuses. Indeed, the circumference of each semilunar valve is normally divided into three equal 120° sectors, and *the aortopulmonary contact point* is easily and consistently locatable and helps identify the site of one *(joining or adja-*
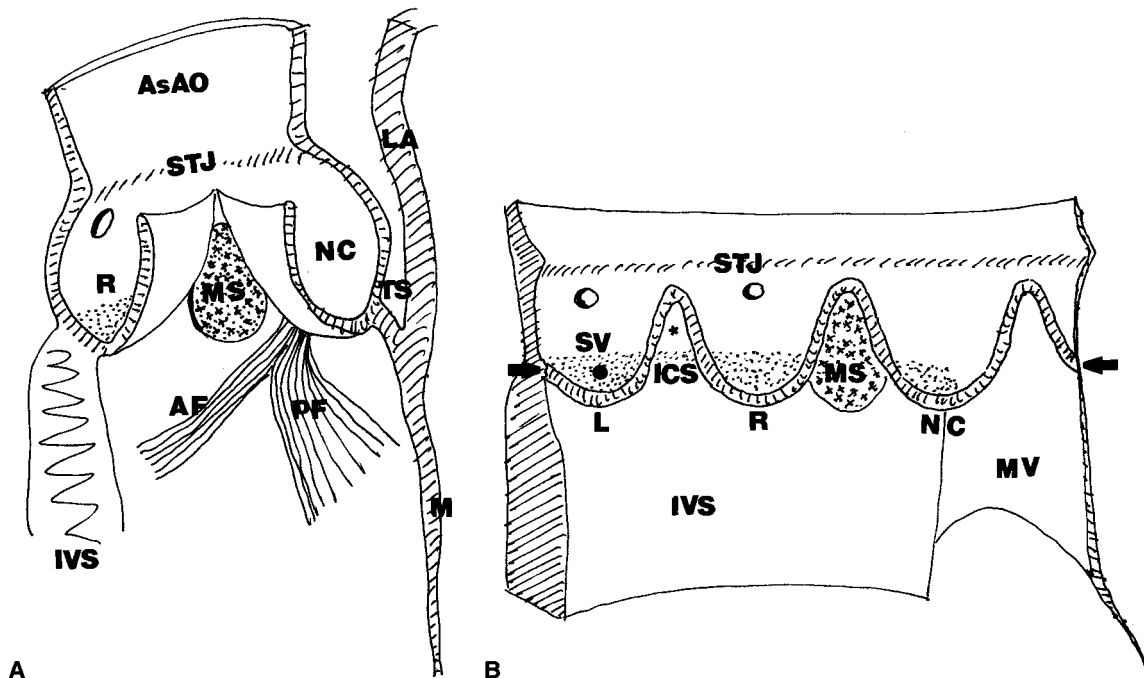

FIGURE 4.3. A and **B.** Diagrammatic representation of the aortic root in cross-section (grossly sagittal, view **A**) and in rectified form (unrolled root, view **B**), after excision of the semilunar cusps to reveal the implantation line of the cusps (view **B**, arrows). The aortic root is limited distally by the sinotubular junction. The sinuses of Valsalva are limited distally by the sinotubular junction and proximally by the implantation line of the cusps. The bottom section of each cusp is shadowed to indicate the underlying muscular septum (view **B**, solid circle). The intercuspal triangles or spaces (view **B**, asterisk), have different wall constituents depending on the specific location. View **A:** AF = anterior fascicle of the bundle of His; AsAO = ascending aorta; IVS = interventricular septum; LA = left atrial wall; M = section of mitral valve; MS = membranous septum; NC = so-called noncoronary sinus; PF = posterior fascicle of the bundle of His; R = right sinus; STJ = sinotubular junction; TS = transverse septum. View **B:** ICS = intercuspal space or triangle; IVS = interventricular septum; L = left sinus; MS = membranous septum; MV = anterior leaflet of the mitral valve; NC = so-called noncoronary sinus; R = right sinus; STJ = sinotubular junction; SV = sinus of Valsalva. **C.** Relationship between the aortic root and the right ventricular cavity. AO = aorta; AP = anterior papillary muscle of the tricuspid valve; AR = anterior right pulmonary cusp; C = crista supraventricularis; MB = moderator band; P = posterior pulmonary cusp; R = raphe of the right ventricular outflow tract (a residual sign of the fusion line between the embryologic conal ridges); RA = right atrial anterior wall; SM = crista septo-marginalis. Shaded area = membranous ventricular septum.
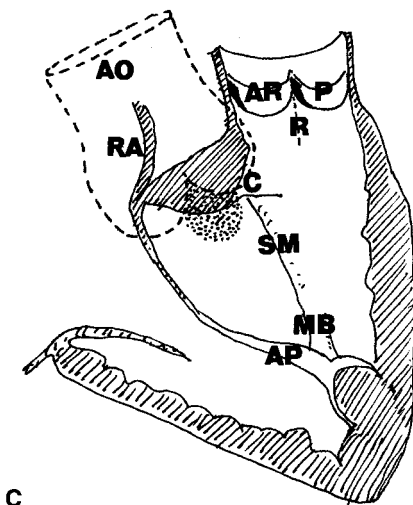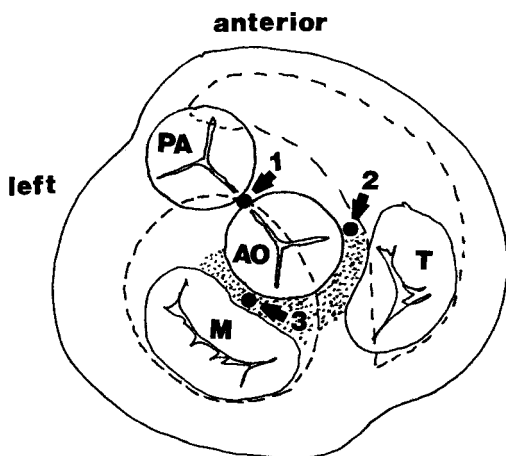
FIGURE 4.4. Schematic representation of the base of the heart (coronal plane) after removal of the atrial walls and the ascending aorta/pulmonary artery. At site 1 the pulmonary annulus is adjacent to the aortic annulus, representing a remnant of the aortopulmonary embryologic septum: This is the consistent site of the anterior commissure of the aortic valve and the posterior commissure of the pulmonary valve. Site 2 indicates the position of the membranous septum. Site 3 shows the relationship between the aortic annulus and the mitral and tricuspid annulus, as well as mitral-aortic continuity. The interrupted lines indicate the approximate positions of the left and right ventricular cavities. AO = aorta; M = mitral valve; PA = pulmonary valve; T = tricuspid. The shaded area represents the sinus transversus pericardii.

cent) aortic and pulmonary commissure (Fig. 4.4). In the normal aortic valve, this commissure is termed anterior or left anterior; in the pulmonary valve, however, the adjacent commissure is called posterior or right posterior.

The two aortic sinuses that adjoin the aortopulmonary contact point are the site of origin for the great majority of the coronary arteries, whether their anatomy is normal or abnormal. The right and left anterior sinuses are called the *"facing sinuses,"* because they face the pulmonary artery. According to traditional teaching, coronary arteries never originate from the sinus opposite the aortopulmonary contact point (the nonadjacent, nonfacing, or right posterior sinus). Therefore, this aortic sinus is also referred to as "noncoronary." In reality, however, coronary origination from the noncoronary sinus has been observed in a few rare cases (see page 46), some of which have been reported in the literature.

The three aortic valve cusps and sinuses have been variably labeled. In Nomina Anatomica (1989),[530] the aortic valve leaflets and sinuses are called *posterior, right, and left.* However, the terms *noncoronary, right (coronary), and left (coronary),* are in widespread clinical use. We encourage the use of topographic descriptive terminology: *right posterior, right anterior, left anterior, and right posterior* (so-called noncoronary). In this approach, the relative location of the cusps is determined with respect to the orthogonal planes, in the coronal plane of the heart (Fig. 4.4). Especially when

describing the coronary anatomy by means of angiography, one would also consider the vertical (superoinferior) axis. In this orientation, the aortic sinuses are not all located at the same level; instead, the left anterior sinus is slightly higher than the others, and the right posterior sinus is slightly lower. Indeed, the anterior commissure of the aorta (which adjoins the aortopulmonary contact point) is the highest point of the aortic valve annulus (Fig. 4.5). The (embryologically conjoined) planes of the aortic and pulmonary valves are slightly different, and they are oriented not horizontally but obliquely, with an anterior lift that causes the pulmonary valve to be slightly higher (more cephalad) than the aortic valve (Fig. 4.5). In any given case, the anatomy of the aortic root should be specifically analyzed and mentioned, never just assumed to be normal, especially when one is describing a coronary anomaly.[141,165,176,194,202,227,348,390,440]

The compact myocardium, which forms during initial embryologic development, from an earlier myocardial structure characterized by a mostly trabecular spongy architecture, cannot grow and function in the absence of a coronary artery system (see Chapter 2). On full development, each myocardial fiber is surrounded by a close network of arteriolar and capillary branches.[499] In the normal human heart, most of the myocardial mass belongs to the left ventricle, and both coronary arteries (left and right) primarily serve the left ventricular mass. Myocardial organization is the fundamental determinant of the anatomy of the distal coronary artery tree. In any coronary anatomic pattern, the potentially modifiable features generally relate to the *proximal coronary segments* (which have a *conductive function*) rather than the *arteriolar segments* (which have a *resistance-modulating function*) or the *capillary segments* (which have a *nutritive function*). For this reason, the following discussion deals essentially with the conductive segments.
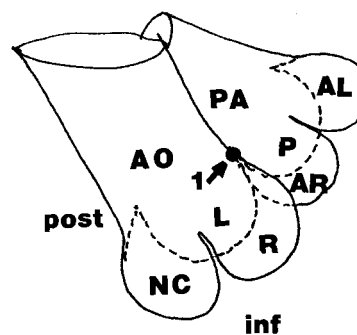

FIGURE 4.5. Relationships between the aortic sinuses and the pulmonary sinuses, as seen in the right anterior oblique projection. The aortic valve annulus is oriented obliquely (tilted anteriorly and superiorly), as is the pulmonary annulus. 1 = the contact point between the aortic and pulmonary sinuses. The left aortic sinus (L) is higher than the right (R) and the noncoronary (NC) sinuses. The antero-left (AL, nonadjacent) pulmonary sinus is located at a higher level than the anterior right (AR) and posterior (P) pulmonary sinuses (the adjacent or facing sinuses). AO = aorta; inf = inferior; PA = pulmonary artery; post = posterior.

Origination of the Coronary Ostia

Normally (i.e., in more than 1% of individuals), *the human coronary arteries have two or three coronary ostia.*[421] Whereas two ostia (the right and left) are typically present, it is also normal to see a separate aortic ostium for a conal or infundibular branch, or third coronary artery,[350] which is present in 23 to 51% of normal hearts.[191,351,508] Less frequently, separate origination of the LAD and circumflex arteries from the aorta, in the absence of a common left main trunk, produces a third (or fourth) coronary ostium. This condition was studied by several anatomists, and the reported frequency of absent left main trunk varied from 0.4 to 8.0%, depending on the criteria used by the different investigators.[94,192,351,391,413,508] If the defining criterion is minimal evidence of a common left main trunk, however rudimentary, like a common aortic niche, the lower estimates are correct. In contrast, if the criterion is absence of a clearly individualized common trunk, the higher estimates are correct. The question of whether an absent left main trunk is an anomaly or a normal variant will be discussed again later in this chapter.

The coronary ostia are normally located in the middle of the right anterior and left anterior sinuses, just above the upper free margin of the semilunar leaflets (in the open position) and just below the sinotubular junction. This general rule applies to cases involving two, three, or even four coronary ostia. As already suggested in the literature,[19,23,227,413,480] a specific, detailed anatomic study needs to be undertaken with the aim of establishing, in a large human population with normal hearts, the spectrum of coronary ostial distribution in both the horizontal plane (oriented along the circumference of the aortic annulus) and the vertical plane (oriented along the longitudinal axis of the ascending aorta). Only after a precise description becomes available can the standard deviations in the two axes be determined and anomalies be exactly defined (Fig. 4.6).

Normally, *the proximal segment of a coronary artery arises at a nearly orthogonal angle from the aortic wall*
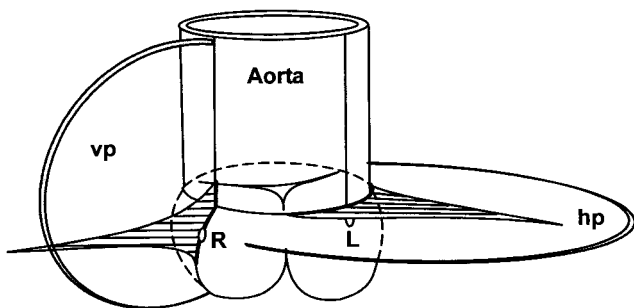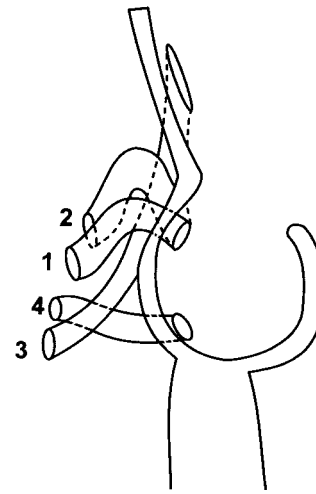

FIGURE 4.7. Cross-sectional view of the right coronary cusp, showing four examples of variant coronary origination: 1, normal, grossly orthogonal to the aortic wall; 2, uplifted; 3, downward with a tangential path (in a case of ectopic origination from the ascending aorta); 4, horizontal (in a case of low, ectopic origination).

(Fig. 4.7). This angle has never been precisely studied in a large population, and the normal range has never been established, but it is important that distinctly unusual angles of coronary origination be recognized, especially during selective catheterization in clinical studies. Coronary ostia that originate ectopically are consistently associated with acute (*"tangential"*) arterial origination from the aortic wall, and only rarely does acute angulation occur in the context of a normal ostial location.

In size, *the coronary ostia are typically equal to, or larger than, the proximal segment of the related coronary artery.*[301] As *the coronary arteries* produce side branches and progress downstream, they *gradually decrease (but never increase) in diameter.*

The course of the coronary arteries is mostly epicardial, at least in humans, although the *proximal LAD* is intramural in 5 to 25% of cases, producing a systolic narrowing or milking effect when observed angiographically (see Intramural Coronary Artery). *The coronary arteries normally terminate in the capillary network* via arteriolar segments, which are responsible for most of the coronary tree's hemodynamic resistance (see Overview of Coronary Physiology). Direct coronary artery communications with the cardiac cavities or with veins are considered generically abnormal (see Anomalies of Termination: Coronary Fistulas).

Although an *ideal "coronary luminal size/dependent myocardial mass ratio"* no doubt exists, its normal range has been difficult to define.[175,205,230,233,247,281,301,408,428,499] It is important that this ratio be clarified, however, to better elucidate anomalies such as coronary ectasia, coronary aneurysm, coronary hypoplasia, or absent coronary artery. The current open debate about how to define these entities stems from the lack of universally accepted parameters of normal

FIGURE 4.6. Schematic representation of the aortic root and the ascending aorta, showing the conceptual pattern of distribution of the right (R) and left (L) coronary ostia in the vertical (for the right) and horizontal (for the left) planes (vp and hp, respectively). See text.

coronary size. Indeed, the absolute coronary artery diameter increases with age[247] and is greatly influenced by the pattern of "coronary dominance." Use of the criterion of relative diameter ratio (>150% of the diameter of the neighboring "normal" segment of the same artery[371]) to define coronary ectasia presupposes that a normal segment is present and recognized, which is not always true in a given case.[230] A more practical, acceptable approach to defining normal coronary size may be based on measurements of coronary flow velocity at rest and after maximum vasodilation, since it is clinically impractical or impossible to obtain an anatomic quantitative description of the distal capillary bed. Gould[145] proposed that a given flow velocity at rest and a maximal flow reserve (ability to increase blood flow with maximal vasodilation) of x4 to x5 with respect to baseline is evidence of normal epicardial coronary size (flow velocity) and arteriolar vasodilatory capacity (functional reserve), respectively. Before valid general statements can be made, however, larger studies must be performed in this regard. Gould's approach would imply that a coronary segment with a decreased flow velocity suggests coronary ectasia, while an increased flow velocity would suggest either a localized stenosis or a hypoplastic segment (congenital stenosis?). Mild forms of coronary hypoplasia (at any level), involving a diminished maximal flow reserve (but a normal flow at rest), may indeed exist as a substrate accounting for some cases of the poorly defined entity known as syndrome X (myocardial ischemia without coronary stenosis). A similar mismatch has been proposed as the mechanism for cardiomyopathy in an experimental model of chronic ventricular overload.[14] Definitive studies need to be undertaken in this regard (see also Coronary Hypoplasia). Generally, we can state that *it is normal for all myocardial segments to have a congenitally adequate arterial circulation with respect to basal and exercise requirements,* and any apparent deviations (such as "absent" coronary artery) should generally have an alternative cause—either ectopic origination of a vessel, which can be difficult to demonstrate angiographically, or acquired vascular occlusion in the absence of demonstrable collaterals (see Absent Coronary Artery).

The normal anatomic features of each coronary artery and its main branches are detailed in the following pages.

Right Coronary Artery

Normally, *the RCA arises from an ostium located just below the sinotubular junction, in the middle of the right anterior sinus of Valsalva, and courses into the right atrioventricular groove.* If the right anterior cusp has more than one ostium, the additional ostium—and there may be more than one[508]—is related to a conal (or more precisely, infundibular) branch. In terms of a *minimal identifying descriptor,* the *RCA* is defined as that vessel which *courses in the right atrioventricular groove and provides nutrient branches to the right ventricular free wall.* (In cases of congenital atrioventricular discordance or situs inversus, the right atrioven-

tricular groove is the groove related to the anatomic right ventricle). In the absence of preexisting literature on this subject, we propose that the artery in the right atrioventricular groove be named the RCA *if it reaches the acute margin of the heart.* On the other hand, if it produces only a few anterior right ventricular branches and does not reach the acute margin of the heart, the lone right-anterior-cusp artery should be called the *infundibular* (or conal) *branch.* Such a condition is usually associated with a large left coronary system, in which the left circumflex artery reaches the acute margin from the posterior aspect of the heart and provides the coronary circulation for most of the heart. In this case, one is dealing with a single coronary artery originating from the left anterior sinus, with the RCA arising ectopically from the distal circumflex artery and an independent conal or infundibular branch originating from the right coronary cusp (see Single Coronary Artery).

In defining the essence of the RCA in these terms, one cannot expect to exhaust the subject of its anatomic variance: this artery may stop at the acute margin of the heart or may continue to the crux or the left atrioventricular groove, ending in the posterolateral left ventricular branch or even the ramus medianus or the diagonal branch and occasionally extending up to the LAD. What is the "normal" maximal extension of the RCA? Because of a lack of prospective ad hoc studies in large populations, a *"very dominant" RCA, terminating in a left posterolateral branch short of the obtuse margin of the heart should be considered the extreme (largest normal) variant.* An RCA that provides branches to the obtuse margin (and beyond) should be considered abnormal, and this condition should be called "anomalous origination of the circumflex artery from the distal RCA." It is also normal for an RCA to provide a posterior descending branch that follows the posterior atrioventricular groove as far as the apex of the heart but not beyond.

In summary, the dependent territory of the normal RCA may vary: at one extreme, the artery may just reach the acute margin of the right ventricle; at the other extreme, the artery may stop just short of providing an obtuse marginal branch (Fig. 4.8).

Descriptions of the right and circumflex arterial patterns have usually been limited to defining the dominant versus nondominant variants, depending on the origin of the posterior descending branch. Indeed, in classifying normal RCA patterns, Baroldi and Scamazzoni[508] included a "type-II" pattern, in which the RCA produces not only the posterior descending but also the obtuse marginal branch. Unfortunately, these authors failed to define the circumflex artery, leaving room for inconsistency. Currently, it would seem crude and inadequate to describe the RCA anatomic spectrum in terms of simple dominance alone, especially in light of practical considerations related to anatomic-physiologic correlations (using echocardiography and nuclear myocardial scintigraphy) and therapeutic interventions (bypass surgery and catheter angioplasty). Ideally, a map of the left ventricular myocardial mass, including the interventricular
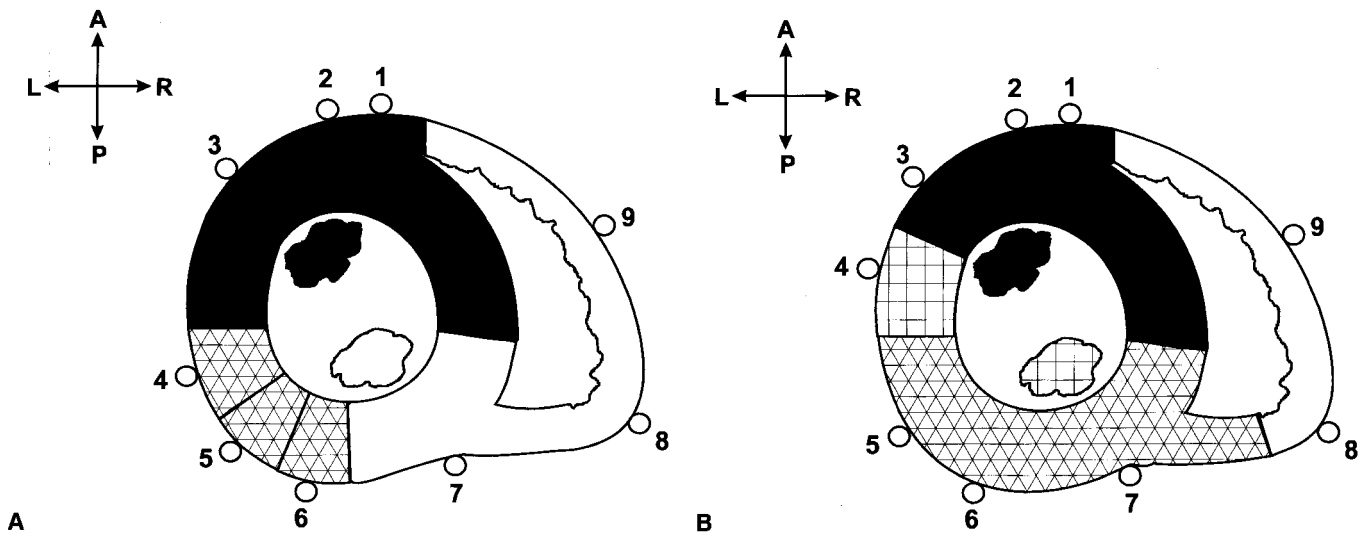
FIGURE 4.8. Horizontal cross section of the heart showing the myocardial segments supplied by the LAD (black), RCA (white), circumflex (triangles), and ramus medianus (squares) in cases of dominant RCA **(A)** and dominant circumflex **(B)**. The numbered circles around the sections represent the location of individual coronary branches: 1 = LAD; 2 = second diagonal; 3 = first diagonal; 4 = obtuse marginal (case **A**) or ramus (case **B**); 5,6 = further obtuse marginal branches; 7 = posterior descending artery; 8 = acute marginal; 9 = anterior right ventricular branch. The section of the papillary muscles is shown inside the left ventricular cavity.

septum, should be constructed to indicate the respective territories of the RCA, LAD, and circumflex artery (Fig. 4.8). For clinical angiographic purposes, we support the policy of describing the coronary artery patterns and distributions, including detailed mention of the main secondary branches (as small as about 1.5 mm in diameter), according to their territorial distribution (Fig. 4.8). In most cases (about 90% in humans), the RCA is "dominant," meaning that it generates a posterior descending branch, which provides blood flow mainly to the posteroseptal left ventricular myocardium, past the proximal, predominantly conductive section of this vessel, which gives off only small branches to the free wall of the right ventricle. One of the RCA's terminal branches, which originates at the crux of the heart, provides nutrient flow to the atrioventricular node. That terminal branch may facilitate angiographic location of the interventricular septum, as the atrioventricular node is situated in the cephalad, posterobasal portion of the interventricular septum, just underneath—and in front of—the coronary sinus's opening into the right atrium (Eustachian valve).

Normally, *the RCA does not provide branches that cross the anterior interventricular sulcus* into the left ventricular territory. A small septal (interventricular) branch may originate from the proximal RCA or directly from the right anterior cusp by means of an independent ostium.

Of the multiple small, highly variable atrial branches that may arise from the RCA, the sinus node artery is the one most commonly recognized. Nevertheless, its origin and course vary widely. In 50% of cases, the sinus node artery arises from the proximal RCA. In the remaining cases, it branches from the proximal circumflex or mid RCA.[192,508]

The other atrial branches have a highly variable, unpredictable morphology. Individually, they are generally considered unimportant for clinical purposes, with the possible exception of a branch that follows the crista terminalis (the line of separation between the smooth posterior section of the right atrium and the highly trabeculated anterior portion).

Left Coronary Artery

The LCA originates from the middle portion of the left anterior sinus of Valsalva, just above the level of the free edge of the open aortic cusp and just below the sinotubular junction. The exact site of the left coronary ostium varies. Specific studies should be undertaken to identify the value of two standard deviations in the distribution curve of the left coronary ostial site, as proposed in the case of the RCA (Fig. 4.6). *The left coronary ostium is usually single,* so it is normal to see a common LCA trunk. In an ad hoc review of 1950 consecutive selective coronary angiograms (see pages 38–43), the authors documented absence of a left main coronary trunk (with double orifices, and separate origination of the circumflex and LAD arteries) in less than 1% of cases, a finding that defines this condition as a coronary anomaly. A proximal coronary vessel originating from the left ostium is called the left main stem or trunk only if it gives rise to both the LAD and the circumflex artery. In anomalous cases, in which one of these arteries does not originate from the LCA, the trunk that arises from the left anterior sinus should be called not the left main but the proximal LAD or circumflex artery, whichever is appropriate.

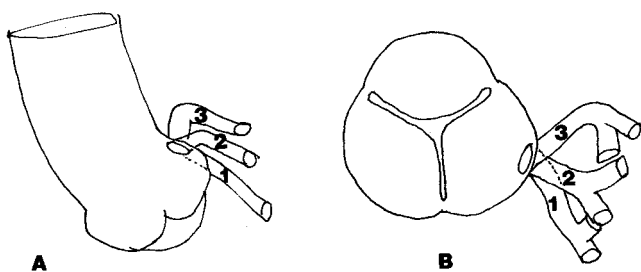Because the left main coronary trunk arises orthogonally

FIGURE 4.9. Schematic views of left coronary variants, in the frontal **(A)** and horizontal **(B)** planes, showing different orientations of the left main trunk: in **A**, inferior tilt (A1), normal orthogonal tilt (A2), and superior tilt (A3); in **B**, anterior tilt (B1), normal orthogonal tilt (B2), and posterior tilt (B3).

from the aortic sinus, it usually lies in the coronal plane of the heart. Occasionally, the left main trunk may be oriented more anteriorly or posteriorly, superiorly or inferiorly (Fig. 4.9). Again, specific studies are needed with regard to the spectrum of normal variation in left main trunk orientation.

Because the left main trunk is only a short (conductive) arterial segment, from which the circumflex and LAD arteries normally spring, and because the latter vessels are the two main nutrient components of the LCA, some experts have proposed that *the LAD and circumflex* be termed *"arteries"* and that the farther, *secondary ramifications,* such as the diagonal or medians, be called *branches or rami.*[508]

Despite the great variability in the morphology of the LCA system, the following fairly consistent rules may be set forth.

- *The LAD courses in the anterior interventricular groove, the circumflex artery in the left atrioventricular groove.*
- The LAD gives off branches to both the septum and the anterolateral wall of the left ventricle, including the anterolateral papillary muscle, and the circumflex artery produces branches to the posterolateral wall of the left ventricle, usually including the posteromedial papillary muscle (Fig. 4.8).
- The LAD terminates *at* the cardiac apex, or 1 to 2 cm *before or after* the apex.
- The anterior septal branches (perforators) originate from the LAD, at the anterior interventricular sulcus, at a grossly perpendicular angle with respect to the cardiac surface; these branches immediately become intramural, coursing within the ventricular septum.
- The LAD seldom produces sizable branches (i.e., large enough for bypass surgery or angioplasty) that extend to the free wall of the right ventricle, but it does frequently produce smaller branches, which are directed toward the anterior wall of the right ventricle. These branches may become more prominent if collateral circuits are established between the LAD and RCA, involving both the proximal segment (Vieussens' circle) and the distal segment of the LAD. In the latter case, the collaterals connect the anterior ventricular or acute marginal branches of the RCA with the distal LAD.[349–351]

- The diagonal branches, which, in human adults have a luminal diameter of >1.5 mm, consist of one to three independent vessels that arise from the LAD at variable downward angles and course over the anterolateral free wall of the left ventricle. Anatomists and angiographers customarily call "first diagonal" the first branch that arises from the LAD in its downstream course. Conversely, surgeons prefer to use the term "Diag-1" for the first branch encountered lateral to the LAD and "Diag-2" for the next branch, which has a more lateral course (Fig. 4.10). In the future, this nomenclature should be rendered uniform by a universal agreement.
- The terms "ramus medianus," "intermedius," or "intermediate branch" refer to a coronary branch that covers a variable extent of the free wall of the left ventricle, posterior to the territory of the diagonal artery and anterior to the first obtuse marginal branch of the circumflex artery. Therefore, *the "ramus medianus" is defined as the intermediate vessel between the first diagonal and first obtuse marginal branches.* In some hearts, no sizable vessel fits this definition. The origination site does not define the nature of the ramus medianus, because this vessel may occasionally arise from the proximal LAD or directly from the left main or proximal circumflex artery. The obtuse margin of the heart is neither a precise anatomic feature (Fig. 4.8) nor an angiographically recognizable entity but a useful approximate term for identifying a point or line in the free wall of the left ventricle. Moreover, unlike the anterior or posterior interventricular groove, the obtuse margin is not a consistent site for a large epicardial coronary branch. Therefore, one occasionally has trouble determining which branch to call the ramus medianus, and in a sizeable number of cases (30%?), experienced observers will agree that this vessel is missing.
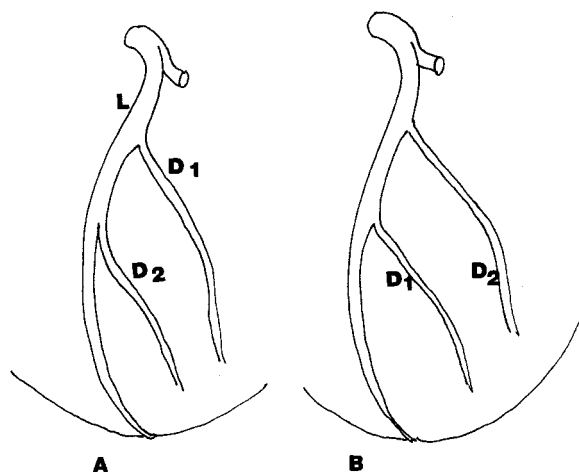

FIGURE 4.10. The alternative nomenclatures generally used by angiographers and anatomists **(A)** or by surgeons **(B)**. See text. D_1 = first diagonal branch; D_2 = second diagonal branch; L = LAD.

- The circumflex artery runs along the left atrioventricular groove, descends beneath the left atrial appendage, and courses downward toward the crux of the heart for a variable distance. *An LCA that has a circumflex artery that does not reach the crux of the heart is customarily called "nondominant." An LCA that has a circumflex artery that reaches the crux and produces the posterior descending branch,* along the posterior interventricular groove (Fig. 4.8), *is called "dominant."* In reality, however, "right and left dominance" is a poor term because, as James[192] noted, the LCA is larger than the RCA in most normal hearts, even when the RCA provides the posterior descending branch. Current terminology referring to dominance should be replaced by nomenclature that describes the posterior interventricular septum's blood supply or its distribution, avoiding any reference to literal "dominance." In addition, it is important to realize that the circumflex artery and the RCA are not the only arteries that can participate in vascularizing the posterior third of the interventricular septum; another possible participant is the LAD, which may not end at the apex but, rather, may turn around it and then follow the posterior interventricular groove for a variable length. For further discussion of this point, see page 58.
- It is probably useful to define *the "minimal circumflex artery"* as that vessel which *provides at least one branch to the territory of the obtuse margin.* In cases in which the LCA's territory does not extend to the obtuse margin, one would expect the circumflex artery to originate ectopically (usually from the RCA), and the LCA would be considered an LAD in the absence of a common left main trunk.
- Atrial branches commonly originate from the circumflex artery (especially those branches directed to the left atrium, but sometimes also those directed at the right atrium and the sinus node's territory). Such branches less frequently arise from the left main trunk, and they never arise from the LAD. In some 40% of normal hearts, the artery to the sinus node originates from the proximal circumflex artery.[192,508] The atrioventricular node artery may originate from the circumflex artery, but only if the latter artery reaches the cardiac crux, usually with a dominant pattern.

In considering the wide spectrum of epicardial coronary artery patterns in normal human hearts, one can arrive at the following basic conclusion: in all hearts, any left ventricular myocardial segment has essentially the same amount of arterial supply (measured by capillary density) as any other segment, but the proximal arterial vessels can be organized into a great number of alternative patterns. A proper, uniform, widely accepted system of nomenclature must be established to promote reliable interobserver communication, which is especially important from the clinical standpoint.

INCIDENCE OF CORONARY ANOMALIES: ANGIOGRAPHIC ANALYSIS OF 1950 CASES

The recent literature contains several reports about the incidence of coronary anomalies, either in the general patient population or in patients with clinical evidence of myocardial ischemia. These reports involve both angiographic and autopsy series. Some of them specifically concern the incidence of coronary anomalies in young persons,[85,106,241] athletes,[254,514–518,534] soldiers,[245] patients recovering from an acute myocardial infarction,[37,143,424] those suffering sudden death,[393,513,520] or those studied by angiography for suspected coronary artery disease.[21a,76,77,196,197,206,406,430,437] Unfortunately, the entry criteria and methodology used by the different investigators are poorly described and variably defined, yielding unreliable figures that are not strictly comparable.

A higher incidence of coronary anomalies has been consistently observed in young victims of sudden death than in adults undergoing routine autopsy examination (incidence: 4 to 15% versus about 1%, respectively). The medical community still hesitates to accept these differences at face value, however, because the reporting centers tend to have a particular, well-recognized interest in congenital coronary anomalies; therefore, the incidence of these rare entities is probably artifactually heightened because of a referral bias. In addition, the results depend on whether certain relatively common entities such as muscular bridges are specifically investigated and counted as coronary anomalies.

To help clarify the incidence of coronary anomalies, our group at the Texas Heart Institute evaluated selective coronary angiograms obtained from 1950 consecutive patients with documented or suspected coronary artery obstructive disease and otherwise normal hearts.

Patients and Methods

Materials and Techniques

Coronary angiograms performed in 2000 consecutive cases between January and May 1989 were retrieved from the archives of St. Luke's Episcopal Hospital's cardiac catheterization laboratories and were prospectively reviewed according to the criteria described herein. Fifty angiograms were excluded because they either were nonselective or did not adequately show all of the expected coronary vessels. The remaining 1950 angiograms were technically satisfactory and, therefore, were included in the study. The population included adult patients (1369 men and 581 women) with an average age of 56.7 years (Table 4.1).

In the great majority of cases, multiple projections had been obtained by means of the Judkins technique, using preformed right and left coronary catheters. In a minority of cases, alternative catheters (mainly the Multipurpose or Am-

TABLE 4.1. *Demographics of the patient population (Total n = 1950)*

Patient group	Number	Percentage
Patients with coronary artery disease	1290/1950	66
Patients without coronary artery disease	660/1950	33
Men	1369/1950	79
Women	581/1950	21
Men with coronary artery disease	1019/1369	74.4
Women with coronary artery disease	271/581	46.6

platz right or left coronary preformed curves) were used after the primary catheters failed to allow selective catheterization. Such failure occurred with greatly increased frequency in cases of coronary anomalies, especially when the coronary ostium was juxta-commissural or tangentially oriented with respect to the aortic wall. Although the brachial approach entailed less frequent need for a secondary catheter, even in the presence of anomalous coronary origination, this approach was used in less than 10% of cases.

In almost all cases, Renografin® or Hypaque-76® was injected as a contrast medium. Unlike the currently more popular low-osmolar media, Renografin and Hypaque have slightly better contrast characteristics. They cause more severe transient bradycardia, allowing better definition of the myocardial blush phase of coronary angiography and, therefore, better definition of the dependent myocardial territory.[224]

Criteria for Describing the Angiographic Anatomy of the Coronary Tree (Fig. 4.11)

We specifically and systematically studied the following coronary angiographic features:

Origin

To elucidate the relationship between the coronary ostia and the aortic sinuses, we examined the morphology of the coronary sinuses (best seen in the right anterior oblique orientation with a 30° cranial tilt or in the left anterior oblique orientation with a 30° caudal tilt); the vertical level of the coronary ostia in the aortic root, with respect to the bottom of the aortic sinus and to the sinotubular junction or ridge; and the orientation of the proximal coronary stems (variants: normal, tangential). To adequately describe these features angiographically, it was often greatly advantageous to dispose of nonselective injections at the cusp. (Such injections are not routinely performed in clinical studies.) In most cases of coronary anomalies, however, some nonselective contrast injections were necessary because of the initial difficulty of selectively cannulating unusual, unexpected ostia with routine preformed angiographic catheters.

Proximal Coronary Trunks

When the proximal trunks of the RCA, LAD, and/or circumflex artery were combined into a single vessel, they were called mixed trunks and were labeled as follows: RCA-circumflex, RCA-LAD, RCA-LAD-circumflex, LAD-RCA, or LAD-RCA-circumflex.

Course

In describing anomalies of origination, the proximal course of a coronary artery is frequently an open question. Therefore, the relationship between the coronary arteries and other cardiac structures (mainly the atrioventricular and semilunar valves) was studied by inference, and the coronary courses were observed in different angiographic projections to reconstruct their tridimensional anatomy.[185] In some cases, a catheter was positioned in the pulmonary artery for reference. In complex cases, simultaneous right and left ventriculography, or at least biplane aortography, was available.

Coronary Patterns

The myocardial territories of distribution of the coronary branches were studied by inference. The examination focused on the following main features:

1. Left main trunk. The presence or absence of a left main trunk was defined by the presence or lack of visualization of the circumflex or LAD during injection of the ostium of the opposite artery (the LAD or circumflex, respectively). Angiograms were excluded if they involved excessive subselective positioning of the catheter in any of the two left branches. Some reflow in the aortic sinus was necessary to rule out artifactual studies.

2. The LAD branch was identified by its anterior course and multiple septal penetrating branches, not necessarily by its diagonal branches. The diagonal arteries were defined as secondary branches that typically, but not necessarily, originated from the proximal segment of the LAD and spread over the anterior and lateral wall of the left ventricle, next to the anterior interventricular groove artery (the LAD). The diagonal artery may also have originated from the left main trunk, the circumflex, or the ramus medianus.

3. The posterior descending branch was identified on the basis of its multiple posterior septal penetrating branches.

4. The atrioventricular node artery was noted as an indicator for the posteroinferior edge of the interventricular septum (the location of the atrioventricular node). By itself, however, this branch was not considered capable of identifying the dominant artery, which was assumed to be the vessel(s) that supplied the posterior descending arteries with their posterior septal branches (Fig. 4.12).

5. Specific attention was dedicated to the blood supply of the intraventricular septum during the late phase of
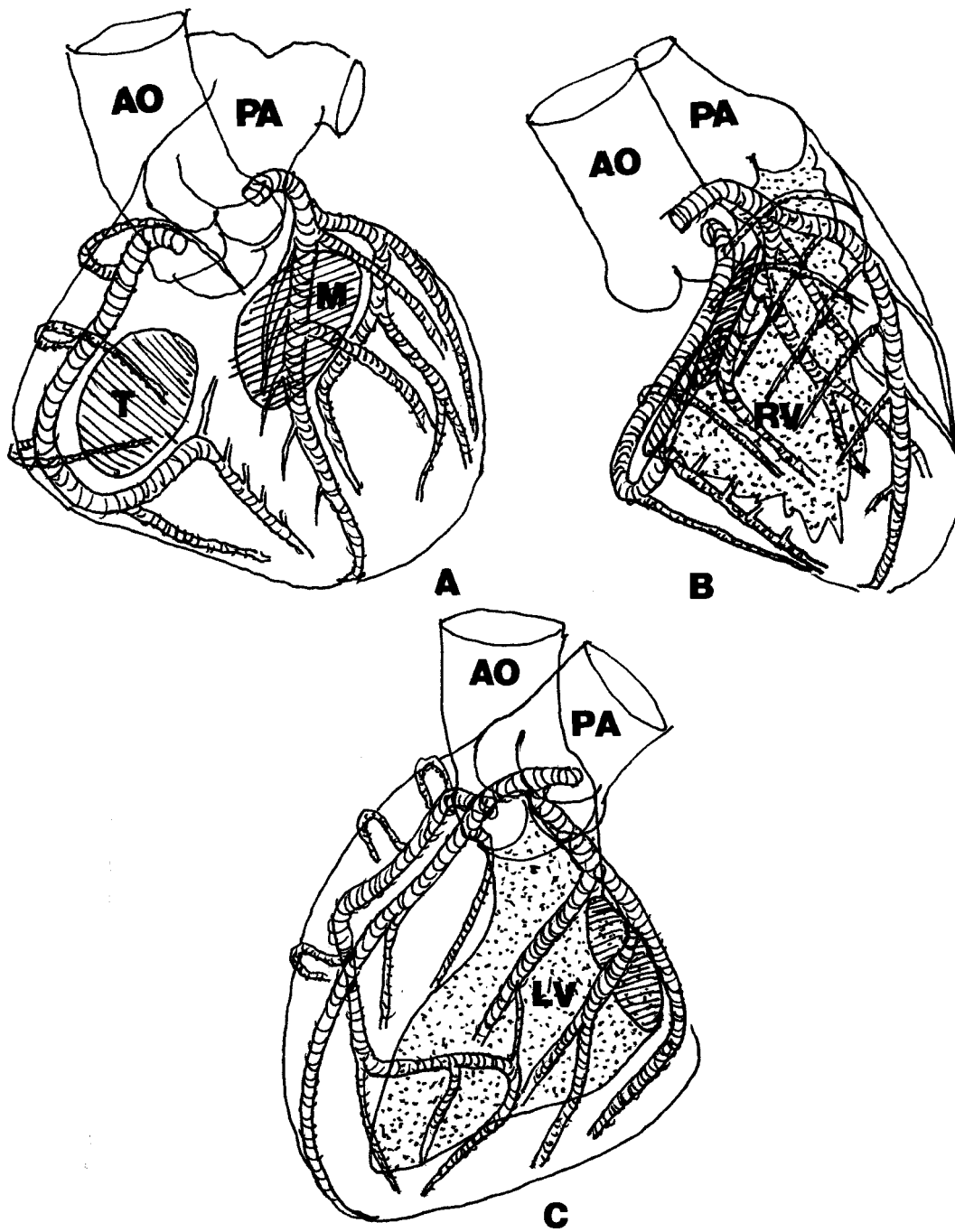
FIGURE 4.11. Relationship between coronary arteries and cardiac structures as seen in the frontal **(A)**, right anterior oblique **(B)**, and left anterior oblique **(C)** projections. AO = aorta; LV = left ventricle; M = mitral valve; PA = pulmonary artery; RV = right ventricle; T = tricuspid valve.
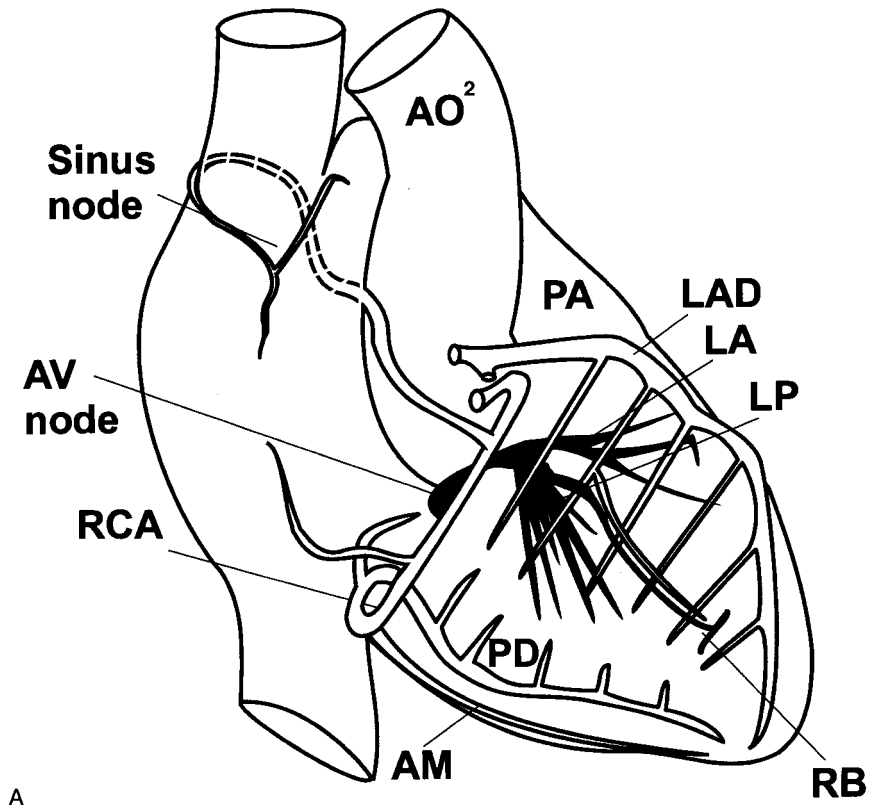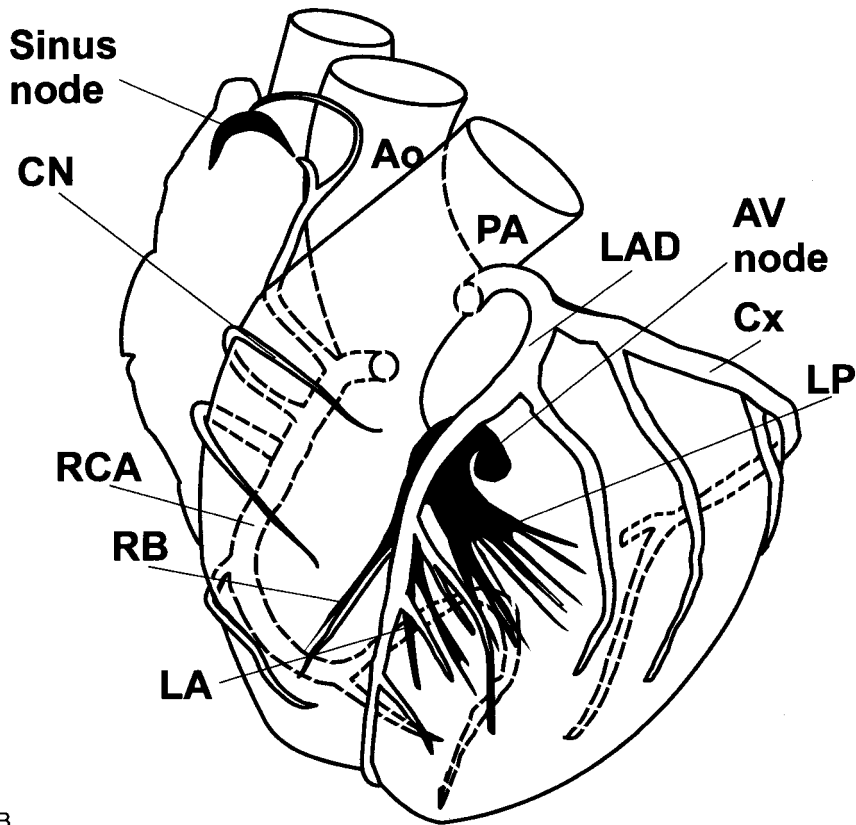
FIGURE 4.12. Right **(A)** and left **(B)** anterior oblique views of the main coronary branches and related cardiac structures. Abbreviations: AM = acute marginal artery; Ao = aorta; AV = atrioventricular; CN = conal branch; Cx = circumflex artery; LA = left anterior fascicle of the left bundle branch; LAD = left anterior descending artery; LP = left posterior fascicle of the left bundle branch; PD = posterior descending branch; PA = pulmonary artery; RB = right bundle; RCA = right coronary artery; SN = sinus node.

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coronary angiography, when myocardial blushing is frequently seen, especially in the left anterior oblique projection, during angiography of both the LCA and the RCA.

6. The obtuse margin of the heart (left ventricle) was identified by recognizing the border of the heart in the left anterior oblique projection (at about 45°; see Figures 4.8 and 4.11). The circumflex artery was identified as the vessel that coursed in the left atrioventricular groove, crossing the obtuse margin of the heart. The larger lateral wall branches, starting from the obtuse margin and moving posteriorly toward the posterior descending artery, were labeled the obtuse marginal 1 (OM1), obtuse marginal 2 (OM2), and obtuse marginal 3 (OM3).

7. Right coronary branches. We used the following nomenclature for right coronary branches:

   a. "Infundibular (or conal) branch" (Fig. 4.12) was used to designate branches that serve the anterior free wall of the right ventricular outflow tract (grossly the 3- to 5-cm segment of myocardial territory below the pulmonary valve). These branches may have direct independent aortic origination. Because infundibular branches that originate separately are usually smaller than the tip of the diagnostic catheter, selective catheterization of such independent branches was rarely observed.

   b. "Right ventricular branch" was used to designate branches that serve the free wall of the inlet and the apical portion of the right ventricle. We tried only to identify the acute marginal branch as the artery that lies closest to the acute margin of the heart. The acute margin of the heart was identified angiographically as the lowest point in the "C" described by the RCA in the left and right anterior oblique views (Fig. 4.12).

   c. "Posterior descending branch" was used to designate the branch that follows the posterior interventricular groove and is angiographically identified by the posterior septal penetrating branches (Fig. 4.12). Compared with the anterior septal penetrating branches, the posterior ones are shorter, frequently being similar in length to the penetrating branches in the free wall of the left ventricle. For this reason, our favored means of identifying the posterior descending branch (and, hence, the dominant artery) was the myocardial blush phase during coronary angiography in the left anterior oblique projection, especially with a caudal tilt, when available. We used the term "codominant circumflex and RCA" for cases in which two branches, one from each of these arteries, coursed into the posterior descending groove, providing septal perforators (Table 4.2).

   d. "Posterolateral" was used to designate branches that provide flow to some portion of the posterolateral wall of the left ventricle, extending as far as the ob-

TABLE 4.2. *Incidence of coronary anomalies and patterns, as observed in a continuous series of 1950 angiograms*

Variable	Number	Percentage
Coronary anomalies (total)	110	5.64
Split RCA	24	1.23
Ectopic RCA (right cusp)	22	1.13
Ectopic RCA (left cusp)	18	0.92
Fistulas	17	0.87
Absent left main coronary artery	13	0.67
Circumflex arising from right cusp	13	0.67
LCA arising from right cusp	3	0.15
Low origination of RCA	2	0.1
Other anomalies	3	0.27
Coronary dominance patterns		
Dominant RCA	1641	89.1
Dominant LCA (circumflex)	164	8.4
Codominant arteries (RCA, circumflex)	48	2.5

LCA = left coronary artery; RCA = right coronary artery.

tuse margin and sometimes including the posteromedial papillary muscle (Fig. 4.8).

Correlations (Table 4.3)

After identifying the variant anatomic patterns, we related them to the following variables: sex, the presence of coronary disease (criterion: >50% obstruction of vessel with a lumen larger than 1.5 mm), the presence of a primary cardiomyopathy (myocardial systolic dysfunction in the absence of coronary disease and/or a clinical history of myocardial infarction able to justify contractile dysfunction). Coronary anomalies were classified according to the scheme

TABLE 4.3. *Correlations*

Variable	Number	Percentage
Men with coronary anomalies	66/1369	4.82
Women with coronary anomalies	44/581	7.6
Patients with CAD and coronary anomalies	63/1290	4.96
Patients without CAD and coronary anomalies	57/1950	8.6
Patients with aortic valve anomalies	75/1950	3.8
Patients with aortic valve anomalies and coronary anomalies	20/75	26.7
Patients with cardiomyopathy	96/1950	4.92[a]
Patients with cardiomyopathy and coronary anomalies	5/96	5.2[a,b]
Patients without cardiomyopathy but with coronary anomalies	105/1854	5.7[b]

[a] P = .90 (NS)
[b] P = .85 (NS).
CAD = coronary artery disease

described in the section entitled Coronary Anomalies, as summarized in Table 4.4 in the Coronary Anomalies section.

Results (Tables 4.1 through 4.3)

Coronary artery obstructive disease was present in 1287 patients (66%) (Table 4.1). The incidence was greater in men (78%) than in women (40%) ($P < .0001$). Coronary variants were identified in 110 individuals (5.6%) (Table 4.2). Such variants were more common in women (7.6%) than in men (4.8%; $P = .008$) (Table 4.3). Primary myocardial impairment (hypokinesia in the absence of obstructive coronary lesions) was not observed more frequently in patients with coronary anomalies (5.2%) than would be expected in the general population. Seventy-five patients (3.8%) had aortic valve disease that was probably of congenital origin, based only on asymmetry of the aortic sinuses. In 20 (27%) of these cases, coronary variants or anomalies were also present. The incidence of coronary variants was significantly higher than that encountered in the patients with coronary artery obstructive disease (4.9%; $P <.0001$) or in the series as a whole (5.6%; $P <.0001$). The incidence of coronary anomalies seemed to be mildly increased in the patients without coronary disease (8.6%; $P = .001$) compared to those with coronary disease. A dominant RCA pattern was present in 89.1% of the general population. The circumflex artery was dominant in only 8.4%, and codominance (RCA, circumflex) was observed in 2.5% (Table 4.2).

Discussion

The most frequent coronary variants (Table 4.2) were split RCA or double posterior descending artery (1.23%) and anomalous origination of the RCA from an ectopic site close to, or at, the right anterior aortic sinus (1.13%) (Table 4.2). These were the only two variants that were present in more than 1% of the cases. According to the "more than 1% incidence" criterion, these morphologies should be considered normal variants.

Because absence of a common left main trunk was observed in only 0.67% of the cases, this pattern should be considered a coronary anomaly, at least as defined by our angiographic criteria. Coronary fistulas were seen in 0.87% of the cases: these were usually small, multiple fistulas that opened into the left ventricle. Admittedly, many of the cineangiograms had too short a running time to identify some of the smaller fistulas. Ad hoc prospective studies may indicate that small coronaro-cameral fistulas (see pages 60–63) are present in more than 1% of normal hearts.

A similar case may be made with regard to muscular bridges. In our series, such bridges were encountered in only five cases (0.003%), but this variant is detected with much increased frequency when more precise, prospective angiographic and anatomic techniques are used (see pages 56–57). Specific angiographic studies intended to rule out myocardial bridges should include multiple views of the LAD (at

least) after intracoronary nitroglycerin administration,[11] which was not routinely done in our series.

In previous angiographic studies reported in the literature, the total incidence of coronary anomalies has ranged from 0.2 to 1.5%, and the frequency of individual anomalies has varied, mainly because of the use of different methods and study criteria.[76,96,206,435] The fact that we detected coronary anomalies on 5.6% of our angiograms was primarily related to the meticulous, prospective quality of our analysis.

Our study had two main intrinsic limitations. First, coronary angiography does not always allow the accurate detection (or exclusion) of some anatomic features that may be relevant for describing normal human coronary arteries. We especially allude to the exclusion of certain associated congenital heart anomalies that may affect the coronary morphology to a greater or lesser extent. Whereas coronary angiography can reliably exclude major congenital defects such as transposition of the great vessels or common truncus arteriosus, this modality may fail to detect minor aortic valve anomalies.[227] We were especially interested in identifying abnormal aortic valves, as there is a notable association between anomalies of the aortic sinuses and those of coronary origination.[227,348] We elected to analyze the coronary patterns in patients who had structurally normal hearts, but minor congenital anomalies of the aortic valve may have been overlooked.

The study's second limitation was that, in our patient population, the usual indication for coronary angiography was clinical evidence of coronary artery obstructive disease or presumption of such disease. It is theoretically possible that congenital anomalies indeed predispose patients to coronary artery disease; if so, our population did not represent the general population. For this reason, we separately analyzed the incidence of coronary artery disease in both the subset with coronary anomalies and the larger population with normal coronary patterns. Despite these limitations, we thought that an angiographic ad hoc analysis was the only practical way to assess the frequency of coronary anomalies in a large clinical series. Autopsy studies of a large series would have been quite difficult and expensive to carry out.

As seen in Table 4.2, less frequent anomalies were also encountered in our series: some of these and other anomalies observed by the authors over the last several years are the object of the angiographic atlas of coronary anomalies that accompanies the following systematic discussion.

CORONARY ANOMALIES

Table 4.4 presents a list of coronary anomalies that aims at being comprehensive and rational but is yet historical and nontheoretical. Additional coronary anomalies could potentially occur, but we have never encountered such anomalies and are unaware of any descriptions of them. Examples could include (1) anomalous origination of the LAD from a posterior septal perforator and (2) anomalous course of a

TABLE 4.4. *Classification of coronary anomalies in (normal) human hearts*

A) Anomalies of origination and course
  1) Absent left main trunk (split origination of LCA)
  2) Anomalous location of coronary ostium within aortic root or near proper aortic sinus of Valsalva (for each artery):
    a) High
    b) Low
    c) Commissural
  3) Anomalous location of coronary ostium outside normal "coronary" aortic sinuses
    a) Right posterior aortic sinus
    b) Ascending aorta
    c) Left ventricle
    d) Right ventricle
    e) Pulmonary artery Variants:
      1) LCA arising from posterior facing sinus
      2) Cx arising from posterior facing sinus
      3) LAD arising from posterior facing sinus
      4) RCA arising from anterior right facing sinus
      5) Ectopic location (outside facing sinuses) of any coronary artery from pulmonary artery
        • From anterior left sinus
        • From pulmonary trunk
        • From pulmonary branch
    f) Aortic arch
    g) Innominate artery
    h) Right carotid artery
    i) Internal mammary artery
    j) Bronchial artery
    k) Subclavian artery
    l) Descending thoracic aorta
  4) Anomalous origination of coronary ostium from opposite, facing "coronary" sinus (which may involve joint origination or adjacent double ostia). Variants:
    a) RCA arising from left anterior sinus, with anomalous course:
      1) Posterior atrioventricular groove* or retrocardiac
      2) Retroaortic[a]
      3) Between aorta and pulmonary artery[a]
      4) Intraseptal[a]
      5) Anterior to pulmonary outflow[a] or precardiac
      6) Posteroanterior interventricular groove[a]
    b) LAD arising from right anterior sinus, with anomalous course:
      1) Between aorta and pulmonary artery
      2) Intraseptal
      3) Anterior to pulmonary outflow or precardiac
      4) Posteroanterior interventricular groove

  c) Cx arising from right anterior sinus, with anomalous course:
    1) Posterior atrioventricular groove
    2) Retroaortic
  d) LCA arising from right anterior sinus, with anomalous course:
    1) Posterior atrioventricular groove[a] or retrocardiac
    2) Retroaortic[a]
    3) Between aorta and pulmonary artery[a]
    4) Intraseptal[a]
    5) Anterior to pulmonary outflow[a] or precardiac
    6) Posteroanterior interventricular groove[a]
  5) Single coronary artery
B) Anomalies of intrinsic coronary arterial anatomy
  1) Congenital ostial stenosis or atresia (LCA, LAD, RCA, Cx)
    a) Coronary ostial dimple
    b) Coronary ectasia or aneurysm
  2) Absent coronary artery
  3) Coronary hypoplasia
  4) Intramural coronary artery (muscular bridge)
  5) Subendocardial coronary course
  6) Coronary crossing
  7) Anomalous origination of posterior descending artery from anterior descending branch or septal penetrating branch
  8) Absent PD (split RCA)
    Variants:
    a) (Proximal + distal) PDs, both arising from RCA
  9) Absent LAD (split LAD). Variants:
    a) LAD + first large septal branch
    b) LAD, double
  10) Ectopic origination of first septal branch
C) Anomalies of coronary termination
  1) Inadequate arteriolar/capillary ramifications?
  2) Fistulas from RCA, LCA, or infundibular artery to:
    a) Right ventricle
    b) Right atrium
    c) Coronary sinus
    d) Superior vena cava
    e) Pulmonary artery
    f) Pulmonary vein
    g) Left atrium
    h) Left ventricle
    i) Multiple, right + left ventricles
D) Anomalous collateral vessels

[a] If a single, common ostium is present, the pattern is considered to represent "single" coronary artery.
Cx = circumflex; LAD = left anterior descending coronary artery; LCA = left coronary artery; PD = posterior descending branch; RCA = right coronary artery.

coronary artery inside the atrial septum. Our proposed classification scheme is based on our own experience as angiographers and a thorough review of the pertinent literature. It stresses a meticulous, orderly approach in which each feature of the normal coronary anatomy is viewed as a criterion for potential anomalies. We prefer to combine the traditional headings "anomalies of origin" and "anomalies of

course,"[115,287] because a coronary artery's proximal course can be abnormal only if that artery's origin is abnormal (except in the case of intramural or subendocardial coronary arteries). Rather than favoring alphabetical-numerical listings, we prefer descriptive, clear terminology that identifies each anomaly. Moreover, we prefer to avoid labeling an anomaly with the name of its purported discoverer.

In this section, most of the descriptions of coronary anomalies are followed by case presentations that illustrate the anomalies' typical features. Because our institution has a limited collection of anatomic specimens, the illustrations are primarily angiographic. Additionally, relevant clinical and functional correlations are presented. A general discussion of the clinical and functional consequences of coronary anomalies is included at the end of this chapter.

The clinical features of major coronary anomalies that tend to manifest in the pediatric age group are described in Chapter 5, which also discusses the surgical treatment of those anomalies.

INDIVIDUAL ANOMALIES OF ORIGINATION AND COURSE

Absent Left Main Trunk (Split Origination of the LCA)

Isolated absence of a left main trunk is defined as that condition in which both the LAD and the circumflex artery originate directly from the center section of the left sinus of Valsalva, without having a common trunk.[94,391] In 2000 consecutive autopsies, Vlodaver and associates[413] found this anomaly in 1% of the cases. In a prospective analysis of a continuous series of 1950 angiograms (see pages 38–43), researchers at the Texas Heart Institute concluded that the incidence of absent left main trunk (as thereby defined) was only 0.55%, suggesting that this entity is properly classified as an anomaly. The left main trunk should also be considered to be absent when the LAD or circumflex artery originates ectopically, outside the left coronary sinus (this condition is known as secondary absence of a left main trunk). On the contrary, when both the LAD and the circumflex artery originate ectopically, an ectopic left main trunk may be present if the LAD and circumflex arteries share a proximal, conjoined stem of any length (see pages 50–54). The clinical relevance of isolated absence of a left main trunk appears to be limited,[430] as this anatomic pattern, *per se,* cannot be expected to produce any functional ischemic effect. In cases involving an absent left main trunk, special techniques must be used for selective catheterization and angiography, as mentioned earlier (page 39); moreover, angioplasty of either the LAD or the circumflex artery may necessitate certain technical adaptations. The coronary ostia are usually smaller than would be expected in the presence of a common left main trunk, and the routine preformed guiding catheter may subselectively cannulate the target vessel, resulting in its obstruction. Typically, the Judkins left coronary catheter will selectively cannulate the LAD, and the Amplatz left coronary catheter will tend to cannulate the circumflex artery. In contrast to patients who have a left main trunk, those with an absent left main trunk cannot develop left main stenosis, the most severe form of coronary disease.

(See Case Report 4.1 in the Atlas of Case Reports)

Anomalous Origination of a Coronary Ostium at or Near the Normal Aortic Sinus of Valsalva

As discussed earlier, an exact definition of normal versus abnormal coronary origination from the aortic root would depend on the completion of studies in large populations, which could be done only from an anatomic standpoint. Meanwhile, it seems safe to state that coronary arteries which arise above the sinotubular ridge or junction and/or which are located next to the aortic commissures[234,496] are anomalous, even when located in the vicinity of the expected sites in the proper sinus of Valsalva (Fig. 4.6). A "commissural" coronary ostium should probably be defined as an ostium located less than 5 mm away from an aortic valve commissure (or apex of the intercuspal triangle). In this group of anomalies, "high" origination tends to overlap with ectopic origination from the ascending aorta. We propose that ostia located less than 1 cm "above normal" be included in this group; this classification would be especially valuable for angiographic purposes, since the sinotubular junction often cannot be precisely identified.

A more subtle variation, which usually goes unrecognized, is anomalously low origination within the proper coronary sinus (Fig. 4.7). This condition is recognizable anatomically and angiographically because the involved ostium is located close to the lower rim of implantation of the aortic cusp. Preformed coronary catheters often fail to allow selective cannulation because they are designed to be aimed specifically at the mid portion of the right and left aortic sinuses and, more importantly, because the proximal stems of these ectopic coronary arteries may be tangential[508]—rather than orthogonal—with respect to the aortic wall. Angiographic studies of such anomalies frequently require the use of more than one catheter, multiple injections of a contrast medium (including initial subselective injections to locate the anomalous ostium), and a prolonged catheter manipulation and fluoroscopy time.

In these cases, selective catheterization is especially important, because tangential origination of such ectopic arteries leads to an increased incidence of ostial coronary stenosis (involving atherosclerosis and/or congenital ostial ridges or fibrous thickening), as seen in *Case Report 4.3,* below. Multiple angiographic projections may be necessary for proper visualization of such ostial stenoses. Tangential origination seems to be a definite anatomic risk factor for coronary artery obstructive disease. Otherwise, this anomaly apparently causes no clinical repercussions except for difficult cannulation during coronary angioplasty. However, because aortic valve replacement is usually accomplished via an aortotomy just above the sinotubular junction of the ascending aorta, high origination of the RCA may interfere with this surgical approach. Implantation of the ring of an aortic valve prosthesis should not be hindered if these anomalies are recognized beforehand (especially in cases involving low origination of the RCA).

(See Case Reports 4.2 Through 4.7 in the Atlas of Case Reports)

Anomalous Location of a Coronary Ostium Outside the Normal "Coronary" Aortic Sinuses

Ectopic Coronary Ostium Located at or near the Right Posterior Aortic Sinus (Noncoronary)

The right posterior coronary sinus is commonly termed "noncoronary" because coronary ostia are only rarely, if ever, observed in this sinus.[77,219,285,435,526,527,529] A fundamental condition for including a case in this category is the presence of a normal, trifoliate aortic valve. Some of the patients reported in the literature have had, or could have had, substantial anomalies of the aortic valve, mainly of the bicuspid kind. In most true cases of these anomalies, the ectopic ostium has a commissural location: usually it is the LCA ostium that is located next to the posterior left commissure. In itself, this anomaly is benign unless it involves a tangential origin (as it frequently does), in which case it may carry an increased risk of ostial stenosis and/or enhanced spasticity. During coronary angiography, this anomaly causes difficult cannulation as a result of its unexpected location and its tangential or slitlike nature. When this anomaly is suspected after initial unsuccessful attempts to cannulate, biplane aortography is recommended. The right anterior oblique and straight lateral projections are the most contributory ones for establishing posterior origination of the LCA. The relationship between the ostium and the aortic sinuses should be documented, preferably using the right anterior oblique projection with a cranial tilt and selective injections. For selective catheterization, the operator must be highly skilled and patient.[179,219,300,529] The Amplatz or Multipurpose curved catheters offer the best chance of success. Alternatively, the Sones catheter, advanced from the brachial artery, offers a favorable approach. In addition, intravascular ultrasound has recently been used to identify this anomaly (Fig. 4.13).[527]

This anomaly should be ruled out when selective cannulation cannot be achieved with Judkins left-sided catheters and nonselective angiography shows a longer than usual left main trunk. The anomaly is generally considered benign,[19, 186,411] and the literature contains only one case in which origination of the left main artery from the noncoronary sinus led to a clinical event, namely the occurrence of a large, fatal anterior myocardial infarction in a 12-year-old girl.[529] The mechanism of coronary occlusion in this case was probably clot formation in the slitlike ostium of the anomalous vessel.

In the presence of this anomaly, angioplasty of any LCA's branches would also offer unusual difficulties because of precarious selective cannulation and back-up support.

(See Case Reports 4.8 and 4.9 in the Atlas of Case Reports)

Ectopic Coronary Ostium Arising Outside the Aortic Root, in the Ascending Aorta

An ectopic coronary ostium located outside the aortic root, in the ascending aorta, can be present at different levels but
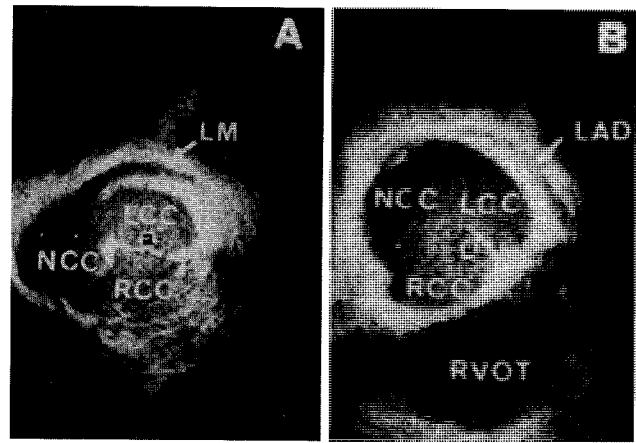

FIGURE 4.13. A. Intraaortic ultrasound image showing the left main coronary artery (LM, white arrow) originating from the square coronary sinus. **B.** The artery courses posteriorly around the left coronary sinus and gives rise to the left anterior descending artery (LAD, white arrow). The ultrasound transducer's position (in the left coronary sinus in view **A** and the right coronary sinus in view **B**) is indicated by the dark central square with the surrounding bright halo of ring-down artifact. The imaging field is scaled by 8-mm divisions. LCC = left coronary cusp; NCC = noncoronary cusp; RCC = right coronary cusp; RVOT = right ventricular outflow tract. (From Lo et al. Anomalous origin of left main coronary artery from the noncoronary sinus: an intravascular ultrasound observation. Cathet Cardiovasc Diagn 1997;42:431. Reprinted with permission.)

usually involves the anterior/left surface of the aorta.[180,201, 234,344,390] In the rare cases reported in the literature, the site of coronary origination has ranged from just above the sinotubular junction to the origin of the innominate artery, several centimeters above the aortic valve. This condition differs from the previously discussed milder anomalies (page 45) in that, here, the ostium is clearly located above the sinotubular region of the aortic root; the ectopic coronary arteries frequently have slitlike orifices and a tangential proximal course along the aortic wall, on which they lie, loosely attached to the aortic tissue. Occasionally, the proximal coronary segment is intramural, inside the aortic wall, and is intussuscepted for 0.5 to 5.0 cm.[325] Once the ectopic coronary artery reaches the epicardial surface, it regains a normal location and course. The RCA is the most frequently ectopic artery, but the LCA (or, separately, the LAD and circumflex artery) may also originate ectopically. Although an ectopic proximal artery course is not a pathologic condition in itself, the artery may be predisposed to have a more active atherosclerotic buildup, especially at the ostium, perhaps because of rheologic factors and unusual shear stress.[409]

Angiography of this type of anomaly is frequently challenging and incomplete. The basic initial condition that should alert the angiographer is the absence of a coronary ostium at the expected site. In such cases, the first step is to rule out ostial atresia or occlusion, as suggested by retrograde filling of the distal "missing" artery from the contra-

lateral ostium or a conal branch. The second step is to rule out necrosis of the dependent myocardium, in which case occlusion without collateral filling could be hypothesized. It is frequently necessary to obtain a biplane aortogram to visualize the anomalous vessel, even though nonselectively. On the basis of biplane aortographic data, the ascending aorta, especially the anterolateral segment, should be probed with special catheters to identify and selectively cannulate the ectopic ostium. The most helpful catheters for this purpose are the Sones, Multipurpose, and Amplatz models (especially the left, with its shorter curve) and only occasionally the routine Judkins catheters. Once the anomalous coronary artery has been selectively cannulated, angiography must be carried out in multiple projections, with special emphasis on those that show tangential views of the proximal segment, to rule out ostial stenosis.

Angioplasty of these vessels can be quite difficult, because of the unusual ostial features (intrinsic obstruction, a slitlike orifice, and a tangential proximal course),[259] which render selective catheterization with the larger guiding catheters unfeasible. During cardiac surgery, coronary arteries of this type may create unexpected problems if the anomaly is unsuspected. To avoid damaging the anomalous artery, the aortotomy should be carried out, after careful dissection of the ectopic vessel, at a higher level than usual, especially during aortic valve replacement.

Because congenital aortic valve anomalies are associated with an increased risk of coronary ectopia (see also Chapter 3), adequate preoperative evaluation by means of selective angiography is mandatory for such aortic valve anomalies, even in the absence of clinical evidence of coronary obstructive disease. Routine echocardiography will rarely identify such anomalies.

(See Case Report 4.10 in the Atlas of Case Reports)

Ectopic Coronary Ostium Arising from the Left Ventricle

To our knowledge, there have been only a few reports[81, 289,464] of origination of the RCA from an otherwise normal left ventricle, just below a congenitally insufficient and/or stenotic aortic valve, in adults (Fig. 4.14). This condition should be strictly defined as origination of a nutrient coronary vessel (providing flow to the myocardium) from the left ventricle. This definition excludes unrelated anomalies such as aorto-left ventricular tunnel and sinusoidal-coronary collaterals. Only in the presence of severe congenital stenosis or atresia, within the spectrum of left ventricular hypoplasia,[163,477,496] do the latter anomalies tend to occur, constituting a venting mechanism for the overloaded left ventricle, as occurs in the right ventricle in cases of pulmonary atresia with intact ventricular septum.[280] In such cases, communication between left ventricular intertrabecular spaces and normally originating epicardial coronary arteries (which may be stenotic or atretic) represents congenital collateral or vi-
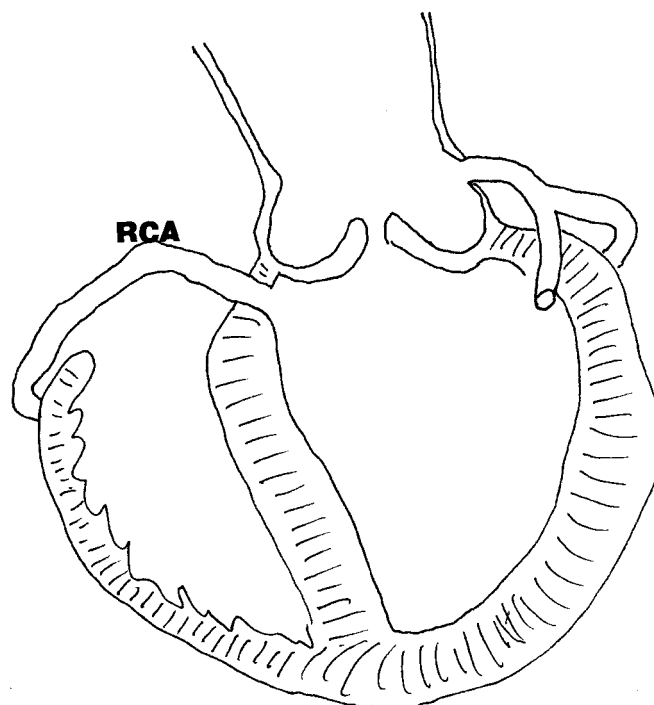

FIGURE 4.14. Schematic diagram showing anomalous origination of the right coronary artery (RCA) from the subvalvular left ventricular outflow tract. This anomaly probably represents the most extreme degree of caudal migration of the right coronary ostium (see Fig. 4.7).

carious circulation[484] and, therefore, should be regarded as a different entity from primary ectopia of the coronary artery.

Especially in the absence of significant aortic insufficiency, the anomalous artery that originates from the left ventricle will be seen to have diastolic flow into the left ventricle, in the presence of collateral flow from the opposite, normally originating coronary artery. In such cases, selective catheterization of the ectopic ostium is expected to be quite problematic. An ischemic effect on the dependent myocardium may be demonstrable, especially by means of nuclear scintigraphy.

Ectopic Coronary Ostium Arising From the Right Ventricle *(see Chapter 6)*

"Origination of a coronary artery from the right ventricle" is usually a misnomer for a complex congenital heart condition in which pulmonary atresia and an intact ventricular septum coexist with multiple right ventricular sinusoids, which functionally drain during systole into the neighboring coronary vessels;[31,129,163] during diastole, however, these sinusoids drain coronary blood to the right ventricle, in competition with nutrient flow to the myocardium (see Chapter 6). This condition has never been observed in an otherwise normal heart.

Ectopic Coronary Artery Arising from the Pulmonary Artery

As a major coronary anomaly that commonly manifests in the pediatric age group,[43,104] ectopic coronary artery originating from the pulmonary artery is more thoroughly discussed in Chapter 5. The present chapter covers general anatomic and nosologic considerations regarding this condition.

Anomalous origination of a coronary artery from the pulmonary artery is defined as that condition in which a coronary artery carrying nutrient flow anatomically arises from the pulmonary main trunk.[49] Indeed, a coronary artery is also connected to the main pulmonary artery (or its branches) in some cases of coronary fistulas.[26] To further confuse this issue, anomalous origination of a conal branch from the main pulmonary artery may result in a condition that resembles a coronary fistula both angiographically and anatomically. Interestingly, in anomalous origination of a coronary artery from the pulmonary artery, the direction of the fistulous flow is toward the pulmonary artery,[8,113,306,318,339,452] as seen in coronary-to-pulmonary fistulas. Nevertheless, in the present condition, blood flow originates from the contralateral, normally originating, coronary artery; whereas in coronary-to-pulmonary fistulas, flow originates from the coronary aortic ostium of the artery that has the fistulous communication.

The following forms of ectopic origination of one or more coronary arteries from the pulmonary artery have been reported.[73,197,277,278,426]

- Anomalous LCA arising from the posterior facing sinus of the pulmonary artery or from the pulmonary trunk or branches (the most common form, abbreviated as AL-CAPA)[467]
- (Isolated) circumflex artery arising from the pulmonary artery (posterior facing sinus) or one of its branches[57,74,169,292]
- (Isolated) LAD arising from the posterior facing sinus of the pulmonary artery[98]
- RCA originating from the anterior facing sinus of the pulmonary artery or from the pulmonary trunk or its branches[102,251,264,378,420]
- Simultaneous RCA and LCA arising from the pulmonary artery[398,451,465,474] (sometimes originating in a single common trunk[503])
- Small (right infundibular or conal) branch arising from the anterior facing sinus of the pulmonary artery

Occasionally, ostial stenosis involving a ridge or fibrous buildup is observed in the pulmonary arterial wall.[252] This condition may significantly decrease fistulous flow.

Anomalous origination of the entire LCA from the pulmonary artery (ALCAPA) has distinct clinical features that are discussed in Chapter 5. In the literature and in clinical practice, several taxonomic classification criteria have been proposed, mainly in response to the clinical need for distinguishing between subtypes of ALCAPA that have different prognostic and therapeutic implications. This anomaly's clinical manifestations and anatomophysiologic forms are not adequately characterized by the terms "infantile" or "adult" or similar fuzzy descriptors (see Chapter 5) but, rather, require a more complex terminology.

ALCAPA varies greatly with respect to clinical presentation, prognostic implications, and the optimal choice and timing of therapy. Its treatment depends on multiple anatomic, functional, and clinical variables, including the following factors:

- The coronary dominance pattern (the larger the RCA, the better the results of simple ligation of the ectopic vessel and the overall prognosis)
- Obstruction of the ectopic ostium (the more severe the obstruction, the better the natural prognosis)
- The extent of acquired coronary artery obstructive disease (the more extensive the disease, the more severe the myocardial ischemia)
- Epicardial versus intramural collateral patterns (the former pattern promotes fistulous flow, and the latter one favors nutrient flow)
- The myocardial oxygen demand (which is related to left ventricular dilation, diastolic volume overload secondary to a left-to-right shunt and mitral regurgitation, and systemic vasoconstriction)
- The pulmonary artery pressure (the higher the pressure, the lower the fistulous flow)[276]
- Body weight and lifestyle factors

Less common, clinically different conditions—anomalous origination of the RCA, LAD, or circumflex artery from the pulmonary artery—are presented here, as they are usually compatible with prolonged, frequently asymptomatic, survival in the adult age group].

Anomalous Origination of the RCA, LAD, or Circumflex Artery From the Pulmonary Artery

Each of these three anomalies has different pathophysiologic consequences and clinical presentations. *Origination of the RCA from the pulmonary artery* has been described in several recent isolated case reports.[117,130,214,226,251,252,264,312,378,387,400,416,420] In most instances, the ectopic ostium was described as being located at the anterior right pulmonary cusp, and the RCA was dominant, with a posterior descending branch. In such cases, collateral circulation between the LCA and the RCA follows the patterns seen in atherosclerotic occlusion of the coronary arteries: the atrial, infundibular, right anterior, and septal branches may contribute to variable degrees in individual cases (Fig. 4.15A). The septal branches are usually the dominant source of collateral flow (from the LAD to the posterior descending artery). These enlarged vessels, with their fistulous flow, are prominently displayed not only during angiography but also during echocardiography with Doppler interrogation (Fig. 4.15). In adults, the condition is typically recognized because of a heart murmur or when angiography is performed for ac-

FIGURE 4.15. Anomalous origination of the RCA in a 36-year-old woman. A strictly systolic murmur was present on precordial auscultation. **A.** Angiogram of the LCA in the right anterior oblique projection (late frame). Residual contrast material is seen in the LCA. The mildly enlarged right coronary artery (R) drains into the pulmonary artery (arrow). LAD = left anterior descending artery. **B.** Transesophageal echocardiogram showing the three aortic valve sinuses (AO), next to the pulmonary artery (AP), from which the right coronary artery (RCA) originates from an anterior-right position. LA = left atrium; RA = right atrium. **C.** Color Doppler image of the ventricular septum in a four-chamber view, showing several sites of high-velocity (fistulous) flow (arrows) within the interventricular septum (IVS). LV = left ventricle; RV = right ventricle. (Photos courtesy of Dr. J. Veselka of Prague, Czech Republic.)
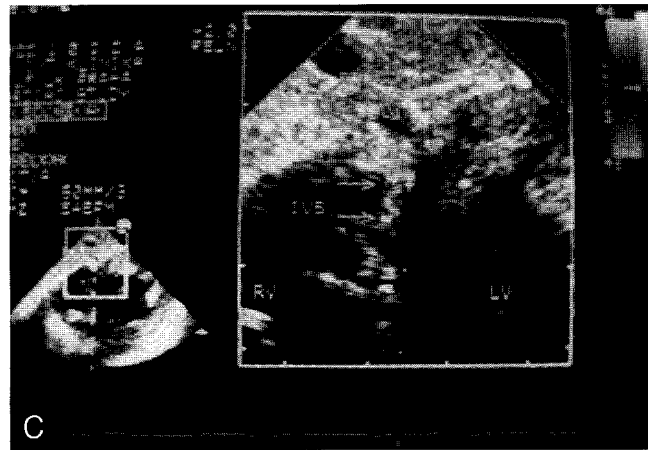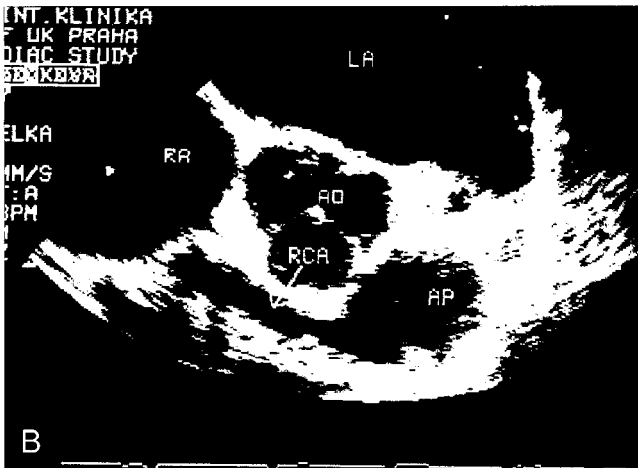
quired coronary obstructive disease, but some patients report angina[214] (frequently atypical) or have silent ischemia, as manifested by a positive stress test without angina.[130] Only in occasional cases does myocardial impairment cause congestive heart failure in patients of pediatric age.[400] Most adult patients with anomalous origination of the RCA from the pulmonary artery have normal left and right ventricular function, and there are no reports of sudden death related to this anomaly. Surgical treatment is similar to that for AL-CAPA; in fact, the first surgical reimplantation into the aorta of an ectopic coronary artery originating from the pulmonary artery involved an anomalous RCA (see Chapter 5). Location of the ectopic coronary ostium in the anterior cusp, adjacent to the aorta (Fig. 4.15B), greatly expedites surgical correction (see Chapter 5), and extracorporeal circulation is frequently not required.

An isolated *circumflex artery*[57,74,169,292] *or LAD*[98,309] may originate anomalously *from the pulmonary artery*. These anomalies are quite rare but are well recognized in the litera-

ture. Each condition is an instance of absent common left main trunk, and only one of the two left-sided arteries is ectopic. Therefore, with respect to its clinical presentation, this condition is much less severe than ALCAPA: the territory at risk for ischemia is more limited, and the sources of collateral flow are more abundant. Indeed, both the RCA and the normally originating left coronary branch provide collateral and fistulous flow. In most cases, the clinical presentation is benign. With LAD originating from the pulmonary artery, only one case of clinical ischemia resulting in a myocardial infarction has been reported.[98] Clinical findings typically include a heart murmur (usually only systolic, but possibly also continuous), atypical angina, and an unexpectedly abnormal stress test or angiogram. Although there are no reports of sudden death related to these anomalies, such an event is surely a possibility, especially during strenuous exertion. The anomalous LAD ostium is commonly located in the posterior left sinus, next to the aorta (in the facing cusps), and can usually be transferred surgically into the

aorta with the aid of extracorporeal circulation and transection of the pulmonary artery (see Chapter 5). The ectopic circumflex artery more typically originates from a pulmonary branch (the proximal right or left), and reimplantation necessitates careful dissection.

Unlike in ALCAPA, the ratio of fistulous to nutrient flow seems to favor nutrient flow, so that myocardial ischemic manifestations tend to be more limited and to occur only with maximal exercise. Frequently, a relatively obstructive ectopic coronary ostium will also limit the fistulous flow. The amount of absolute flow probably perpetuates an intrinsic mechanism of progressive enlargement of the involved vessels.[103]

Although ectopic origination of a coronary artery from the pulmonary artery is routinely subjected to surgical repair, the need for repair has not been well established.[125] In the absence of major clinical manifestations (recurrent angina, myocardial infarction, ventricular arrhythmias, syncope, or aborted sudden death), anomalous origination from the pulmonary artery may not, in itself, be an automatic indication for surgery, especially if the anomalous vessel is a smaller one such as a nondominant RCA or a circumflex artery. In such cases, stress testing is frequently negative for reversible ischemia in adult patients, although mild fixed myocardial uptake defects are frequently found on nuclear images, because of old scar tissue and/or a rich collateral network, which replaces myocardial tissue.[125,264] Progressive enlargement of the dilated coronary vessels, with the risk of intimal changes, mural thrombosis, and/or accelerated atherosclerosis, is a possibility in these cases, just as in primary coronary fistula. This factor tends to encourage early intervention (during childhood or the patient's teen years), because otherwise the extremely dilated vessels with increased flow would be transformed, by surgical correction during adult life, into aneurysmatic vessels with normal flow, yielding a persistently poor prognosis because of the risk of mural thrombosis. After correction of this anomaly, coronary ectasia may undergo reversal in young patients but will not generally do so in older ones. The survival of untreated older patients is an indication, if not proof, of the benign nature of the anomaly in such instances. Moreover, the surgical risks may be substantially greater and the potential benefits fewer in older patients, causing many physicians to prefer continued medical treatment and some surgeons to prefer simple ligation (versus the more complex reimplantation) of the ectopic vessel.

(See Case Report 4.11 in the Atlas of Case Reports)

Ectopic Coronary Ostium Arising from the Aortic Arch, Innominate Artery, Right Carotid Artery, Internal Mammary Artery, Bronchial Artery, Subclavian Artery, or Descending Thoracic Aorta

The literature contains rare reports of extracardiac origination of the coronary arteries from the aortic arch,[63] innominate artery,[86] right carotid artery,[63] internal mammary artery,[329,330] bronchial artery,[63] subclavian artery,[330] or descending thoracic aorta[63] in humans. Most of these reports mention accompanying major congenital heart defects.[63,330] In such cases, the proximal coronary trunk's ectopia reproduces, in humans, the normal coronary pattern seen in various animals (see Chapter 1). Reports of bronchial origination of a coronary artery (see also Coronary-Bronchial Fistula, page 62) should be examined critically: because both the bronchial and the coronary arteries are normally subject to the same systemic pressure, no flow could be expected in the absence of a congenital coronary obstruction or a suprasystemic pulmonary pressure with an inverted patent ductus arteriosus (usually in the presence of a hypoplastic left heart syndrome). In cases of uncomplicated extracardiac origination of the coronary arteries from the systemic circulation, no myocardial ischemic effects are generally expected.

Anomalous Origination of a Coronary Artery from the Opposite, Facing Sinus of Valsalva

As stated earlier, the right, left, LAD, and circumflex coronary arteries are defined by virtue of their territory of distribution, not by their origination.[147] When a coronary artery arises anomalously from the opposite-from-normal sinus of Valsalva, the artery's intrinsic name and nature (or function) remain unchanged, and only its origin and proximal course are anomalous.[208] Of necessity, the artery's proximal course is abnormal in these cases, as the artery connects with the contralateral, in situ vascular network. Because these anomalies are characterized by abnormal origination of an otherwise "normal" coronary artery from the opposite sinus of Valsalva, it is important that the *essence* of a coronary artery (in contradistinction to, and independently of, its *origin*) be clearly defined.

Indeed, conceptually the human heart has not two, but three, coronary arteries: the RCA, LAD, and circumflex. The essence of each of these arteries was discussed previously (pages 35–38), and it becomes clear in light of the spectrum of possible variations described in this section.

The RCA is essentially that artery that courses in the right atrioventricular groove and provides nutritive branches to the free wall of the right ventricle. Branches that supply the right ventricular infundibulum, or conus, often originate directly from the right aortic sinus and are not an essential part of the RCA. The same is true of the sinus or atrioventricular nodal arteries and the posterior descending branch: all of these branches may originate anomalously without changing the nature of the RCA.

Similarly, the LAD is essentially that artery that courses along the anterior interventricular groove and provides perforating branches to most of the anterior ventricular septum. It is not essential that the LAD provide a diagonal branch (although it usually does) or reach the apex, but it is essential for the LAD to course mostly in the anterior subepicardial space. Cases in which a large, entirely intramyocardial first septal artery provides most of the anterior perforating

branches in the absence of an anterior subepicardial artery are regarded as anomalous.

Finally, the circumflex artery is essentially that artery that follows the left atrioventricular groove and provides branches to the free wall of the left ventricle, supplying the obtuse margin of the heart. The precise extent of the essential territory of the circumflex artery is a matter of conventional agreement, and no authoritative (empirical) decision has yet been made in this regard.

In any case of anomalous origination of a coronary artery from the opposite sinus of Valsalva, specific attention should be devoted to the ostial location and anatomy, crossing pathway(s), and pathophysiologic and clinical consequences.

Ostial Location and Anatomy

The anomalous coronary artery originating from the contralateral sinus of Valsalva may arise directly from the aorta. Alternatively, the anomalous artery may arise jointly, by way of a mixed trunk,[419] with the coronary artery that normally originates from that cusp. In such a case, a single coronary artery is generally present. When the anomalous coronary artery has an independent aortic ostium, usually it is adjacent to the ostium of the coronary artery that normally arises from that sinus; moreover, the independent additional ostium frequently has a slitlike appearance[395] and an increased likelihood of intrinsic pathology (Fig. 4.16).[344,532] Occasionally, intussusception of the anomalous proximal trunk into the aortic wall is also observed.[340,384]

Crossing Pathways

After arising from the contralateral sinus of Valsalva, an anomalous coronary artery can take one of at least five (or six) crossing pathways—not four, as sometimes stated in the literature.[323] Each of these paths has a peculiar, consistent topographic anatomy[422,504] (Fig. 4.17).

Path 1 may be labeled *"retrocardiac"* to differentiate it from the "retroaortic" one (both paths being generically "posterior"). The retrocardiac path is located behind the tricuspid and mitral valves, at the posterior atrioventricular groove. It frequently goes unrecognized[40,323,327] but is an important alternative route. When an anomalous RCA takes this course, it constitutes the terminal branch of a superdominant circumflex artery, which reaches the right ventricular infundibulum. This condition is usually classified as "single LCA," since no RCA originates from the right sinus of Valsalva. We object to this nomenclature, because it erroneously suggests that these patients have no RCA. In reality, however, the RCA is perfectly developed, although it has an anomalous pattern *(see Case Report 4.16 in the Atlas of Case Reports)*.

When the circumflex artery[293] originates from the right sinus of Valsalva jointly with the RCA and has a posterior course (behind the atrioventricular valves), the anomalous trunk that extends to the crux of the heart is indeed a mixed
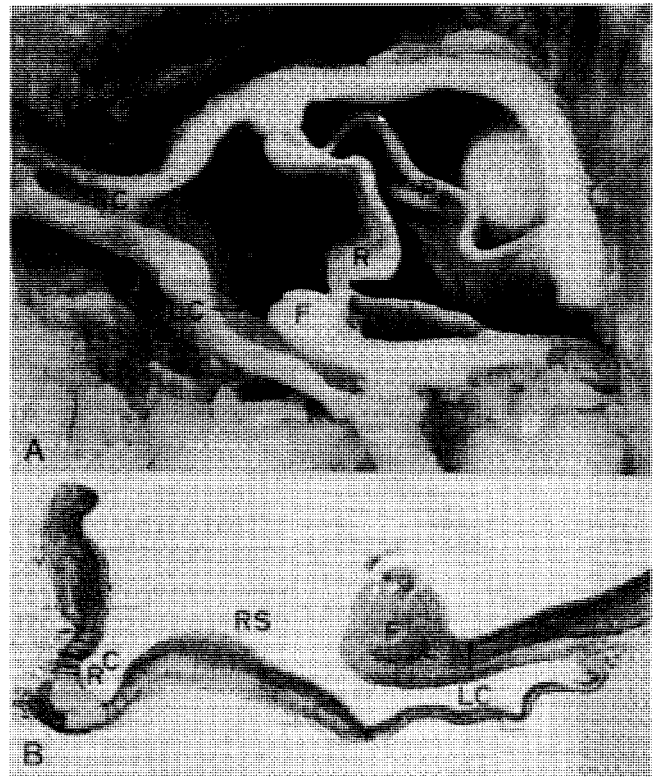

FIGURE 4.16. A. Gross view of a cross-section of the ascending aorta at upper levels of aortic valvular insertions. The right (RC) and left (LC) coronary arteries each arise from the right aortic sinus (RS). As the left coronary artery proceeds toward the patient's left, it makes an oblique angle with the aorta and creates a flap (F) in relation to its ostium. **B.** Section through the same plane as that shown in view **A**, showing the wall of the right aortic sinus from which arise the right and left coronary arteries. The oblique course of the ectopically arising left coronary artery creates, along with the aortic wall, a flap (elastic tissue stain, original magnification x5). L, P, and R = left, posterior, and right aortic cusps, respectively. (From Mahowald et al. Ectopic origin of a coronary artery from the aorta: sudden death in 3 of 23 patients. Chest 1986;89: 669. Reprinted with permission.)

trunk, not a simple RCA.[341] Similarly, the coronary artery that arises from the left cusp is indeed the LAD, not a true LCA, and the left main trunk is absent. Therefore, in such an instance, the diagnosis is absent left main trunk with anomalous origination of the circumflex artery from the distal RCA.

Similarly, the whole LCA may arise from the right anterior sinus jointly with the RCA and have a posterior course behind the atrioventricular valves. In such a case, the proximal trunk is a mixed one, not a "single RCA." The trunk distal to the crux of the heart is indeed an LCA that gives rise first to the circumflex-obtuse marginal and then to the LAD systems. Again, this condition is usually referred to as single RCA, and the above-mentioned objections to this terminology apply (see Single Coronary Artery).

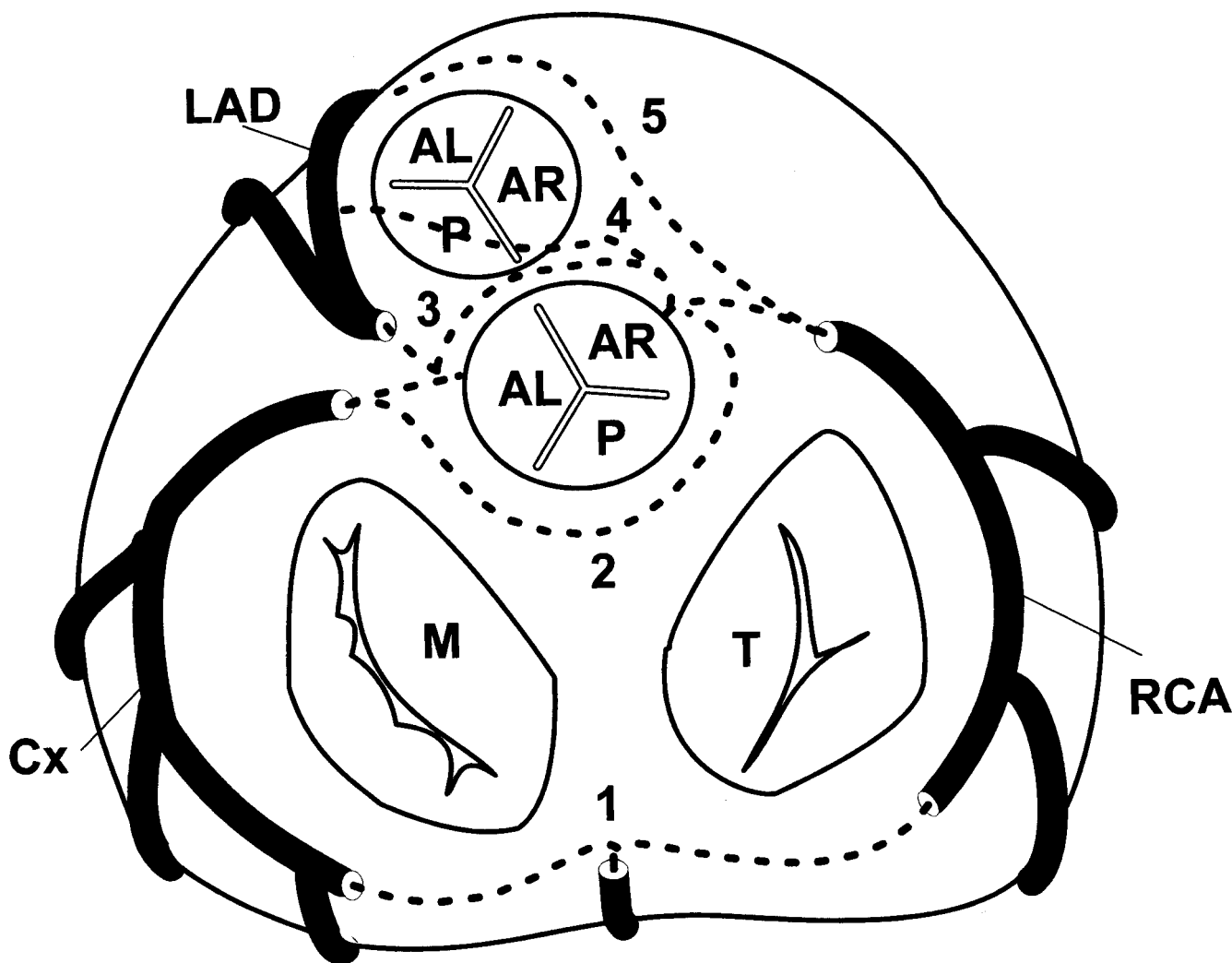*Path 2,* the *retroaortic* anomalous path (Fig. 4.17), is the

FIGURE 4.17. Conceptual diagram showing most of the possible paths (1 through 5) by which the RCA, LAD, and circumflex artery (Cx) can potentially connect with the opposite coronary cusps. Paths: 1, retrocardiac; 2, retroaortic; 3, preaortic, or between the aorta and pulmonary artery; 4, intraseptal (supracristal); 5, prepulmonary (precardiac). The aortic and pulmonary cusps are labeled according to their position in space: AL = antero-left; AR = antero-right; P = posterior; M = mitral valve; T = tricuspid valve.

path most commonly associated with this type of anomaly, specifically involving origination of the circumflex artery from the right sinus of Valsalva.[41,334,365] This anomaly's incidence in the general population ranges from 0.1 to 0.9%,[21a,41] including cases in which the circumflex artery has a separate origin, adjacent to the RCA ostium, and those in which the circumflex artery arises jointly with the RCA from a common short, mixed trunk. The anomalous retroaortic circumflex path courses just next to the posterior wall of the aorta, in the sulcus between the atria and the aorta (the transverse sinus), and finally reaches a normal location in the left atrioventricular groove, providing pathognomonic angiographic features.[41] Cardiac surgeons should be especially aware of this anomalous coronary path, because placement of sutures at the aortic or mitral annulus during valve

replacement might compromise the aberrant vessel. Otherwise, the anomaly, in itself, is not expected to have any clinical consequences.[336]

The same retroaortic path can also be observed, although less frequently,[324] when the RCA originates from the left sinus (either directly or, more often, from a common mixed trunk), and when the entire LCA originates from the right sinus. The retroaortic path is not seen, however, when the LAD has an isolated ectopic origin.

Path 3, the *preaortic* anomalous path, (Fig. 4.17) courses *"between the aorta and pulmonary artery."* This terminology alludes to the fact that an anomalous RCA or LAD or left main trunk (but never the isolated circumflex artery) subepicardially crosses the aortopulmonary septum or space. Embryologically, the aortopulmonary septum is initially in-

tact, formed by the truncal swellings or ridges that subdivide the primitive common truncus. The fact that a coronary artery can be observed to cross the area of the embryologic aortopulmonary septum testifies to the lateness of definition of the proximal coronary anatomy, which occurs well after the completion of truncal septation (see Chapter 1). This path usually entails ostial abnormalities, [213,324,346] but it rarely, if ever, involves systolic compression (unlike path 4, which is intramyocardial).[44]

Recently, crossing of the aortopulmonary septum by the RCA, LAD, or left main artery has been presumed to be the culprit for clinical ischemic manifestations and/or sudden death.[25,32,47,140,159,272,324,335,338,384,494] This subject is addressed in the final section of the present chapter, which discusses the pathophysiologic mechanisms and clinical relevance of coronary anomalies.

Path 4, known as the *intraseptal* path (Fig. 4.17), is mainly located inside the upper, anterior interventricular septum (which embryologically is derived from the conal septum). This path joins the left-sided subepicardial coronary system at the upper anterior interventricular groove, where the LAD meets the aberrant trunk (which never directly joins the left main or circumflex artery). This anomalous path is mostly intramural (intramyocardial) and is frequently recognized angiographically because of its systolic phasic narrowing, as in a muscular bridge.[352,491] Also, the intramural anomalous trunk almost always produces one or two septal perforators that indicate the intraseptal portion of the arterial trunk.[57] In the differential diagnosis based on angiographic data, these two features (intramyocardial course and origin of septal vessels) should be considered characteristic of path 4 (not paths 3 or 5). Whether the anomalous vessel is an RCA,[324] LAD, or left main trunk, it immediately surfaces epicardially on the right side of the heart, beyond the level of the ventricular septum. The anomalous artery then continues until it joins a normal distal RCA (in the case of an anomalous RCA) or an aortic orifice located next to the RCA (in the case of an anomalous LAD or left main trunk). This anomalous path is sometimes called supracristal, but this nomenclature is erroneous, as the anomalous vessel runs behind the crista supraventricularis of the right ventricle and does not directly cross it (Fig. 4.4).

Path 5, also known as the *precardiac* or *prepulmonic* path, is characterized by its subepicardial location, on the anterior wall of the right ventricular outflow tract, or infundibulum. Again, this path may be taken by an ectopic RCA,[263,324,488] LAD, or left main trunk, but never by an isolated ectopic circumflex artery. It is particularly common in patients with tetralogy of Fallot (see Chapter 6), in which the LAD originates ectopically from the right coronary sinus and courses anterior to the hypoplastic, stenotic pulmonary infundibulum. The right-sided point of connection for an ectopic LAD or left main artery is usually the proximal RCA; alternatively, the anomalous artery may connect directly to a supplementary aortic ostium adjacent to the RCA's ostium. If the ectopic vessel with an anterior (prepulmonary) course is

the RCA, it arises from the proximal LAD (not the left main artery), crosses the pulmonary infundibulum, and quickly joins the right atrioventricular groove, regaining a normal course from that point on. The anomalous precardiac vessel frequently gives rise to infundibular but never septal branches.

The presence of a *sixth anomalous path* could be postulated if one considers that the apical route could constitute an alternative origination pathway, as exemplified by cases in which the posterior descending artery originates from the LAD or vice versa (see pages 54–59).

In many cases, the patient will have multiple simultaneous ectopic pathways.[419,498]

Pathophysiologic and Clinical Consequences

This subject is discussed extensively in the last section of this chapter (see Pathophysiologic Mechanisms and Clinical Implications of Coronary Anomalies).

(See Case Reports 4.12 Through 4.34 in the Atlas of Case Reports)

Single Coronary Artery

When a single aortic ostium or origination provides for all of the coronary blood flow, the condition is frequently called single coronary artery.[7,143,167,198,242,283,356,357,360,423,479] It comprises a mixed group of anomalies of coronary origination, already described under other headings, whose only common element is the presence of a single aortic ostium.[40] In the general population, the incidence of single coronary artery is approximately 0.024%,[242,360] so this condition is clearly an anomaly.

In the majority of cases diagnosed as "single left" coronary artery, a thorough anatomic study will reveal that another, small ostium exists in the right coronary cusp and leads to a conal or infundibular branch. In such cases, the diagnosis of single coronary artery is still correct, because the RCA originates (with respect to its essence) from the left ostium. In cases of "single right" coronary artery, no coronary artery, however small, is seen to arise from the left coronary cusp.

The primary classification (and terminology) for single coronary arteries should be based on the location of the single ostium[242,360] (in the right anterior cusp, left anterior cusp, or an ectopic position[180,198]), not on the nature of the single artery itself.[44] Indeed, the anomalous vessel's single proximal trunk should not be designated the RCA or LCA according to the cusp of origination; rather, it should be considered a common mixed trunk, since it gives rise to both the right and left coronary branches, which are labeled (as in a normal coronary tree) according to their respective areas of distribution.[419]

All of the combinations listed in Table 4.5 can occur, and most of them have been reported in the literature. These combinations should be described according to their ostial

TABLE 4.5. *Single Coronary Arteries: Classification Criteria*

Sinus of Origination
1) Right anterior sinus
2) Left anterior sinus
3) Posterior sinus
4) Ectopic sinus, at:
   A) Ascending aorta
   B) Systemic artery
   C) Pulmonary artery
Pathways Followed by Each Ectopic Branch Arising From the Proximal Trunk[a]
1) Retrocardiac (circumflex, LCA or RCA)
2) Retroaortic (circumflex, LCA, or RCA)
3) Preaortic (LCA or RCA)
4) Intraseptal (LCA, LAD, or RCA)
5) Precardiac (LCA, LAD, or RCA)

[a] Any individual case may involve more than one anomalous path.

location, their sequence of origination, and the proximal course of their anomalous coronary branches.[362] Excluded from this list are several conditions that resemble single coronary artery but involve ectopic origination of a coronary artery from the opposite cusp, from an additional ostium adjacent to the normal coronary ostium for that cusp. To conclusively establish the diagnosis of single coronary artery, angiographers and anatomists should verify (1) the presence of a single ostium in one sinus, jointly with the absence of an ostium in the opposite sinus, and (2) the lack of origination of any other coronary artery from an ectopic site. This process is usually quite simple for anatomists but may be harder for angiographers, who may encounter difficulties in ascertaining that the artery in question indeed supplies all of the heart and that no additional ectopic coronary artery exists.

Functionally, single coronary artery has essentially the same clinical implications as ectopic coronary origination from the opposite sinus but with separate ostia; nevertheless, a single coronary artery is not as susceptible to tangential origin or ostial ridge pathology as are ectopic coronary arteries with independent ostia. Coronary blood flow is not affected by the simple presence of a single proximal trunk that supplies coronary flow to the entire heart, unless congenital or acquired obstructive disease is present in the proximal mixed trunk.[22,457] In such a case, the hemodynamic repercussions would be quite severe,[244,423] as the whole heart could become ischemic without having any possible source of collateral circulation. Although definitive studies are not available, the incidence of atherosclerotic disease does not appear to be increased in the mixed trunk. An ectopic single coronary ostium[180,198] could, indeed, be more susceptible to congenital (ostial) or acquired obstructive disease, but the rarity of this anomaly precludes adequate analysis.

During coronary angioplasty, a few minor adjustments are necessary in patients with a single coronary artery.[21,149,375,427] In the presence of a single ostium, even the temporary creation of an ostial obstruction (by means of a large guiding catheter or any other instrument, such as the bulky directional atherectomy device) would be poorly tolerated and could cause symptoms (angina, dyspnea, light-headedness) and important changes in physiologic variables, including blood pressure. In general, angioplasty of the common trunk is absolutely contraindicated, even with the use of stents, not only because of the increased perioperative risk but, more importantly, because of the risk of postoperative restenosis resulting in sudden death (a risk that is expected to be even higher than after angioplasty of the left main trunk).

During coronary artery bypass surgery, the presence of a single coronary artery should not affect any technical decisions, except for suggesting the absolute need for as many arterial conduits as possible. Proximal mixed trunk obstruction is particularly relevant in this regard, because it tends to progress to total occlusion soon after successful bypass surgery. In contrast to venous grafts, arterial grafts are expected to provide longer-lasting conduits. If graft occlusion does eventually occur, it will likely be fatal because of the presence of total occlusion of the native circulation.

ANOMALIES OF INTRINSIC CORONARY ARTERIAL ANATOMY

Congenital Ostial Stenosis or Atresia

The literature contains occasional reports[30,51,139,337,423] of coronary arteries that are atretic[160,455,475,492] or stenosed because of a membrane or fibrotic ridge[195] located at, or near, the aortic orifice in an otherwise normal heart. In cases of atresia, only a dimple is seen from the aortic side.[13] Histologically, when the obstructive element is congenital, it invariably consists of fibrous tissue. A stenosis observed during angiography, surgery, or autopsy may be subject to debate regarding its nature (congenital versus acquired).[139,337] The condition may be associated with a coronary anomaly, sometimes involving tangential origination of a coronary artery.[326,346] Indeed, atherosclerotic growth may occur early in life at the site of a congenital ostial fibrotic plaque.[259] Coronary ostial or proximal occlusion frequently occurs in the context of pulmonary valve atresia with intact ventricular septum (see Chapter 6); in extreme cases, both the RCA and the LAD may be affected by ostial atresia.[396] Isolated coronary ostial atresia (total occlusion) probably represents the extreme degree of improper formation of the aortic ostium, and its presence often raises two questions: first, is the condition congenital or acquired, and second and more importantly, is it truly a case of ostial atresia or is it anomalous origination? The congenital cases could be regarded as instances of neonatally or fetally acquired ostial occlusion, which occurs after a normal distal coronary tree has already developed (however, such occlusion would most likely occur after embryologic development). Ostial atresia in the left coronary system can potentially occur, not only at the aortic connection site but also at the left main bifurcation, the site

of embryologic fusion of the circumflex and LAD arteries with the left main trunk. Collateral circulation to the occluded artery is established prenatally and is provided by neighboring coronary arteries. Unlike anomalous origination of a coronary vessel, this anomaly includes one or more of the following features: (1) more than one (collateral) connection is present; (2) the proximal occluded artery (close to the occlusion) has a larger diameter than the intermediate segment(s) or collateral(s); (3) the proximal anatomy of the occluded vessel is characterized by a cul-de-sac, or blind pouch, that adjoins an aortic sinus; (4) during stress testing, the dependent myocardial territory may show ischemic damage or reversible ischemia, indicating that the obstruction had a relatively late onset and that the collateral circulation is inadequate for maximal myocardial demand; and 5) the site of ostial atresia is sometimes recognizable as a dimple in the related aortic sinus (see the next section).

The fact that myocardial fibrosis and segmental hypokinesia are frequently seen in these cases suggests that early myocardial development may have been normal and that the coronary stenosis or atresia developed or progressed during a later stage of fetal life or during the neonatal period. In cases that involve a primitively atretic proximal coronary artery formation (during the embryologic period), one would expect to find ectopic origination of the affected artery and normal development of the dependent myocardium. Coronary artery "isolation" is a variant of ostial atresia, caused by juxtaposition of an abnormal aortic cusp with the aortic sinus wall, which leads to obliteration of the underlying coronary ostium.[253,500]

(See Case Report 4.34 in the Atlas of Case Reports)

Coronary Ostial Dimple

In the recent literature,[14,361] the term "coronary ostial dimple" has been used for an anomalous finding (a depression in the wall of the aorta at an aortic sinus deprived of functional coronary origination) that may have some embryogenetic implications.[14,361] We refer to cases in which either (1) the sinus opposite the one with the single coronary ostium or (2) the noncoronary (right posterior) sinus in a normal two-coronary heart has a depression in its mid portion that does not lead to a coronary artery.[361] Although this dimple may be the remnant of an embryologic coronary bud,[458] its developmental implications are unclear, especially in light of recent evidence that the primitive coronary network seems to induce penetration into the aortic wall without the independent, active participation of the wall itself (see Chapter 2).

Coronary Ectasia or Aneurysm

In the foregoing discussion of normal coronary artery diameter, ectasia and aneurysm were defined as localized dilations in an otherwise normal-sized coronary artery. Studies in which a Doppler coronary flow wire is used to measure blood flow velocity in coronary aneurysms have helped to characterize ectasia by revealing a significant reduction in peak flow velocity. The possibility should be considered that an eventual decrease in coronary reserve could be related not only to development of acquired stenosis but also (and probably mainly) to the presence of mural thrombosis with distal embolization.[61] Aneurysmal rupture is also a possible complication, especially with larger lesions that have a degenerated arterial wall.[61,109]

Anatomically, ectasia may be divided into two types: primary and secondary. In *primary ectasia*,[46,354] a localized coronary segment has a disproportionately large diameter in comparison to neighboring segments[69,84,162,239,253,255,354, 431,485,487,493,501] and a localized decrease in flow velocity, as indicated angiographically by streamlining and slow runoff of contrast media. Morphologically, ectasia is defined as an increase in the diameter of a coronary segment by >50% with respect to normal.[371] Differentiating primary, congenital ectasia from acquired (atherosclerotic) ectasia may be quite difficult in individual cases.[31,379,380]

In contrast, *secondary ectasia* is characterized by diffuse (global) coronary dilation (with respect to the dependent myocardial territory) secondary to increased or fistulous flow.[103] Here, we are referring not to minor forms of coronary ectasia related to myocardial hypertrophy (such as aortic stenosis or athlete's heart) but especially to the form related to coronary fistulas with greatly increased blood flow. In such cases, the coronary diameter is actually appropriate for the increased flow and is excessive only with respect to nutrient myocardial flow. *The coronary flow velocity is actually increased, not decreased as in primary ectasia.* Additional, disproportionate, localized coronary aneurysmal dilation is typically seen in ALCAPA and in older patients with larger coronaro-cameral fistulas.[85]

Patients with primary or secondary ectasia usually have a highly abnormal intrinsic coronary wall anatomy, with medial degeneration, intimal thickening, and eventually ulceration and mural thrombi.[61,138,209,371,471] Even in patients of pediatric age, congenital primary coronary aneurysms are frequently hard to distinguish from acquired aneurysms resulting from medial degeneration, as in Kawasaki's arteritis.[128,290,522] In adults, the distinction is even more conjectural.[229] Histologic findings are typical only in the acute stages of the disease. A clearly documented history of arteritis and gradual resolution of the coronary aneurysm with time can be considered strong evidence of an acquired etiology.

(See Case Reports 4.8 and 4.11 in the Atlas of Case Reports)

Absent Coronary Artery

This nomenclature is generally a misnomer, used to identify *apparently "missing" coronary arteries or branches*[24, 34,95,178,224] in the absence of adequate documentation. True congenital (embryologic) absence of a coronary artery is expected to lead to hypoplasia of the dependent myocardium as a result of a lack of essential nutrients during embryonic development.[499]

As suggested by R. D. Leachman (oral communication, 1989), some cases of syndrome X (angina and myocardial ischemia in the absence of coronary obstruction) may be caused by a defective number of capillaries per myocardial fiber. This syndrome has never been definitely documented and is not identical with what has been called "absent coronary artery" in the literature.

On angiographic grounds, the most frequent reasons[95] for an apparently missing coronary artery are coronary ectopia (misdiagnosed), coronary occlusion with lack of demonstrable collateral retrograde filling,[225,433] or an alternative coronary artery tree pattern that may not be recognized on angiography. Although the literature includes sporadic cases in which an absent coronary artery was reported to cause chest pain,[178] cardiomyopathy,[34] or a myocardial infarction,[224] absence of a coronary artery has never been established as a specific congenital entity.

(See Case Report 4.6 in the Atlas of Case Reports)

Coronary Hypoplasia

Several reports have appeared in the literature alluding to a poorly defined entity called coronary hypoplasia.[87,137,261, 322,425] Earlier in this chapter, we discussed the difficulty of demonstrating congenital inadequacy of coronary vessel size. Normal coronary arterial size should be defined in terms of both resting metabolic needs and coronary reserve. Epicardial coronary branches normally maintain an ideal luminal diameter ratio with respect to the dependent myocardial bed or territory or capillary network.[205,230,233,281,301] Gould[145] theorized that flow velocity is the most practical parameter for measuring the adequacy of vessel diameter: a higher than normal flow velocity would imply a vessel size that is restricted in comparison to the distal arteriolar-capillary network. However, this type of measurement was previously quite impractical; it became clinically possible only recently, with the introduction of flow velocity wires, and has not yet been used to substantiate the claim of coronary hypoplasia. A more practical diagnostic method may be based on the simultaneous (1) angiographic appearance of a "hypoplastic" coronary branch (that has a small diameter with respect to the apparent area of dependent myocardium) and (2) demonstration of local reversible ischemia (reduced coronary reserve) during stress testing with myocardial nuclear scintigraphy. We are not aware of any cases in the literature in which the diagnosis of hypoplasia could be soundly based on such combined evidence, and any report that portrays a small coronary artery as a pathologic congenital entity[472] should be viewed with skepticism. In most cases, the terminology is used incorrectly, and the dependent myocardial bed is actually served by alternative sources (unusual coronary patterns),[322] or coronary spasm or diffuse disease is present. Roberts and coworkers[322] observed "hypoplastic" right or circumflex arteries in 8 of 3400 consecutive autopsies (0.0024%), according to the dubious criterion of an "absent dominant vessel" (see Absent Posterior Descending Branch).

(See Case Report 4.35 in the Atlas of Case Reports)

Intramural Coronary Artery (Muscular Bridge)

On anatomic grounds, the general rule in human hearts is that large coronary arteries and their branches are situated in the loose connective tissue of the subepicardial space. Nevertheless, the septal penetrating branches are normally intramyocardial, and other usually subepicardial branches are found to be intramural in more than 1% of instances.[68,157,316]

In several mammals and in birds, most of the coronary arteries are intramyocardial (see Chapter 1), apparently without having adverse functional consequences. Three considerations are relevant in defining and discussing muscular bridges in humans: (1) nosologic considerations (what constitutes a muscular bridge? is it an anomaly?); (2) functional considerations (are muscular bridges able to cause disease?); and (3) prognostic considerations (do muscular bridges lead to unexpected pathologic events such as spasm, thrombosis, or atherosclerotic changes?).

An intramural coronary artery[136] is defined as a coronary artery that has a segment of variable length covered by myocardial fibers but that otherwise lies subepicardially.[266] These fibers constitute the "bridge," whereas the underlying coronary segment is not the bridge but, rather, is the "bridged artery." Fine anatomic dissection, with the use of microscopy, has indicated a high incidence of myocardial fibers overriding otherwise subepicardial coronary arteries or branches, as reported in detail by Polacek.[306]

In clinical angiographic studies, detection of the intramyocardial course of a coronary artery depends on systolic compression,[9,307] a narrowing of the lumen ("milking effect") seen during systolic myocardial contraction. Phasic narrowing of a coronary artery may also occur in other conditions, such as in the presence of ventricular aneurysms or pericardial fibrous bands.[10] This angiographic marker is highly predictive of an intramyocardial coronary course, but it is actually seen in only a minority of anatomically detectable cases. Administration of a vasodilator (typically, intracoronary nitroglycerin in a 100- to 300-μg bolus[12,187]) greatly facilitates the angiographic recognition of systolic narrowing. Also, multiple angiographic views of the involved vessel may add relevant information. Systolic narrowing is generally considered to be caused by coronary compression by myocardial fibers that are oriented circumferentially with respect to the heart (and tangentially with respect to the involved vessel). It is usually best seen in projections that are tangential to the cardiac wall over which the involved artery is located *(see Case Report 4.36 in the Atlas of Case Reports)*. A less reliable, indirect indicator of an intramural coronary segment is the "U sign,"[12] caused by the artery's subclinically accentuated descent from its

epicardial location into the myocardium. In more severe muscular bridges, the myocardial bundle over the involved coronary segment is thicker, and the involved artery may be surrounded by circumferentially oriented myofibers.[79,124,265]

With intravascular ultrasonography[12,51,116,134,191] or coronary flow velocity measurements,[116,127,204,352,353,388] it is possible to examine intramyocardial coronary arteries more precisely, because these imaging methods can recognize phasic changes in the coronary cross-section and flow velocity (see Case Report 50, Fig. CR4.50). Unfortunately, the relatively stiff intravascular diagnostic device may cause artifacts both by straightening the artery's U-shaped course and by causing spasm or abnormal compression. According to some recent intravascular ultrasound studies,[12,51,116,191] the systolic milking effect may involve circumferential as well as asymmetric flattening of the vessel, probably depending on the depth of the myocardial bridge.

The question of whether this entity is a coronary anomaly, or an exceptional finding versus a less frequent but normal variant, seems to be answerable on the basis of anatomic and angiographic studies: muscular bridges are present in more than 1% of normal human hearts[11,38,182] and are observed especially often in the presence of ventricular hypertrophy,[11,316] whether it is secondary (aortic stenosis, hypertension), primary (hypertrophic cardiomyopathy)[203] and/or associated with adrenergic stimulation.[133] The proximal LAD is the most common site of muscular bridges,[20,195] and other coronary arteries only rarely have such bridges.[266,362,432]

With respect to the hemodynamic repercussions of an intramyocardial coronary course,[92,93,101,120,158,164,181,210,246,256,305,352,401,417] the discussion is still open. Because an intramyocardial course is normal for large arteries (e.g., septal perforators in humans, and most coronary arteries in many other animals) and because the LAD often has an intramyocardial course without causing ischemic manifestations, this condition should be regarded as only rarely capable of causing pathologic consequences.[50,64,79,196,207,210,491] Unfortunately, the literature contains a large series of poorly documented claims to the contrary.[35,36,59,91,101,119,189,228,257,265,304,405] Of the many patients who undergo angiography because of suspected ischemic heart disease but who do not have fixed obstructive coronary disease, some indeed have a muscular bridge associated with abnormal (usually electrocardiographic) stress test results. This association is especially common in the presence of ventricular hypertrophy, which frequently accompanies muscular bridges and causes nonspecific ST changes in the resting and/or exercise electrocardiogram.

A few authors claim to have demonstrated dependent myocardial ischemia by means of a more specific method, nuclear myocardial scintigraphic stress testing,[33,148,268,274,308,321,319] and some authors have observed relief after coronary stenting or surgical resection of muscular bridges.[5,39,152,166,204,248,257,420,482] Local lactate production during elec-

tronic pacing was also attributed to systolic narrowing, especially during severe tachycardia.[417,482]

Systolic stenosis (which is rarely critical in the absence of maximal, induced vasodilation) is quite unlikely to result in an absolute flow reduction, since 75 to 85% of human coronary flow occurs during diastole, which is not affected by muscular bridges. Indeed, intramural pressure at the capillary level is much more effective at reducing flow than is external, partial compression of a short coronary segment, and it is the intramural pressure that normally modulates phasic flow to the myocardium, even in the absence of a muscular bridge.[168] In a normal heart, during systole, the intramural pressure is higher than the intracoronary pressure[459] (and, hence, the aortic pressure), especially in the subendocardial layers of the left ventricular myocardium, where the capillary bed becomes totally compressed[376]; during systole, coronary flow from the epicardium to the intramural space is abruptly reduced, while flow in the coronary veins is enhanced.[168] In this sense, the left ventricular myocardium normally behaves like a sponge that becomes phasically compressed. Superimposed systolic narrowing of an epicardial vessel cannot greatly change this basic hemodynamic behavior,[210] although such narrowing may cause a minor local disturbance in the phasic dynamics.[135,204] The recent introduction of flow-meter wires has permitted investigators to describe typical phasic changes in instantaneous flow velocity but has not provided reliable data about global blood flow rates.[12,116,127,204,352,353,388]

Still, intramyocardial coronary arteries can have prognostic and clinical relevance with respect to the occurrence of certain rare, potentially important events,[181,183,207] especially coronary spasm (which is only occasionally mentioned in the literature[54,132,153,211,271,358]), thrombosis (which is quite rarely reported[3,121]), and coronary atherosclerotic changes.[112,124,293] Numerous anatomic,[293] angiographic,[182,236,297] and intravascular ultrasound[135] reports document the relatively frequent presence of a coronary atherosclerotic plaque at the proximal bend of an intramural LAD and a consistent absence of intimal changes in the intramural segment.[112,184,223,293,294] In these cases, it is the proximal atheroma (accompanying an intramyocardial LAD) that is the most likely cause of an occasionally positive stress test during myocardial scintigraphy.[271]

(See Case Reports 4.36 and 4.50 in the Atlas of Case Reports)

Subendocardial Coronary Course

In rare cases, the RCA, LAD, or circumflex pursues a subendocardial course after penetrating the myocardial layers.[172,282] In this manner, the LAD may reach the anterior portion of the right ventricular cavity. More frequently, it is the RCA that becomes subendocardial where its posterior, distal segment (just proximal to the crux, in the lower part of the right atrium) adjoins the tricuspid valve annulus.[439] This unusual location of a sizable coronary artery may be more than a

curiosity, especially during surgery for debridging of a coronary artery, or tricuspid valve replacement or valvuloplasty. The literature includes reports of cases in which a simple, nonextracorporeal approach to correcting a muscular bridge of the LAD became a surgical nightmare because of perforation of the right ventricle during unroofing of a segment of the intramyocardial LAD in an unexpected subendocardial location.[90] Unfortunately, no angiographic clues allow this anomaly to be diagnosed before surgery. A subendocardial coronary artery might be viewed as an intermediate stage in a spectrum of "coronary malpositions" ranging from the normal subepicardial location to intramyocardial coronary artery and to coronaro-cameral fistula.

Coronary Crossing

As a rule, epicardial coronary arteries do not cross one another. The literature contains only a few angiographic (but not anatomic) reports[273] that describe crossing of adjacent branches, apparently at the subepicardial level. This phenomenon should not be confused with superimposition of coronary branches during angiography when the vessels lie in different planes. In almost all reported cases and in the few cases seen by these authors, the crossed arteries were obtuse marginal branches. By examining this feature in several angiographic views, the observer can occasionally verify that both arteries are indeed subepicardial (instead of papillary muscles, penetrating coronary branches, or subendocardial collateral vessels). Coronary crossing affects secondary vessels and only rarely causes clinical problems, such as difficulty in identifying a branch to be grafted during coronary artery bypass.

(See Case Report 4.37 in the Atlas of Case Reports)

Anomalous Origination of the Posterior Descending Artery from the Anterior Descending Branch or a Septal Penetrating Branch

According to a consistent rule of coronary morphology, anterior septal penetrating branches do not reemerge on the opposite side of the ventricular septum. In cases of posterior descending artery occlusion, however, they are frequently a source of collateral connection with the facing, posterior septal vessels. Only rarely have cases been reported of an unusually large anterior septal branch that not only penetrates the whole extent of the septum but also reappears, in a subepicardial position, in the posterior interventricular groove, and produces the terminal portion of the posterior descending branch.[55,367] One might doubt the congenital nature of such an anomaly (versus an acquired occlusion of the posterior descending artery with collateral circulation from an anterior septal branch), especially in the context of coronary atherosclerosis. In a more common and clinically relevant pattern, the posterior descending branch originates congenitally from the distal LAD after encircling the cardiac apex (see the next section).

Absent Posterior Descending Branch (Split RCA)

As a rule, the posterior descending branch is a single, continuous vessel that originates from the RCA or circumflex artery, at the crux of the heart, and courses in the posterior interventricular groove. Occasionally, the posterior descending branch comprises two segments: one that originates normally from the distal RCA at the cardiac crux and courses only in the upper posterior portion of the interventricular groove; and another segment that originates from the mid RCA, close to the acute margin of the heart, and reaches the distal posterior portion of the interventricular groove.[147,470] Alternatively, the LAD or circumflex artery may supply part or all of the posterior descending branch, causing it to appear interrupted or split (Fig. 4.18). This phenomenon is a nosologic curiosity, but it may become clinically relevant in surgical grafting of the "posterior descending branch" or while attempting myocardial scintigraphic/coronary angiographic correlations.

(See Case Reports 4.38 and 4.39 in the Atlas of Case Reports)

"Absent LAD"

In the human heart, the anterior subdivision of the LCA (the LAD) generally features anteroseptal and anterolateral (diagonal) branches as it courses along the anterior interventricular groove and tapers toward the cardiac apex. In some instances, a large subepicardial anterior artery is not encountered in the interventricular groove because one of the following alternative patterns is present:

1. The proximal anterior descending artery[100,345] or a supernumerary aortic ostium[296] gives rise to a single large first septal branch that supplies most of the secondary anteroseptal branches, leaving a small or absent mid-distal subepicardial LAD (which is improperly called atretic).
2. The proximal LAD splits into two smaller, parallel branches ("split LAD"),[372] which run along the anterior interventricular groove.
3. A large diagonal artery originates quite proximally from the LAD and runs parallel to it, giving rise to all the anterolateral branches. Beyond the origin of the first septal branch, the residual distal LAD is left with limited dependent territory and appears as a very small vessel, where a bypass graft could not typically be implanted.
4. A highly dominant RCA gives rise to most of the anterior septal penetrating branches by producing an anomalous LAD[177] (via the direct intraseptal[56] or the anterior prepulmonic[40,418] route, unusually prominent posterior septal branches, or a wrap-around-the-apex posterior descending branch).

In similar cases, the small size of the LAD might lead to the erroneous conclusion that the LAD territory is ischemic because of the unusual coronary pattern. In the absence of
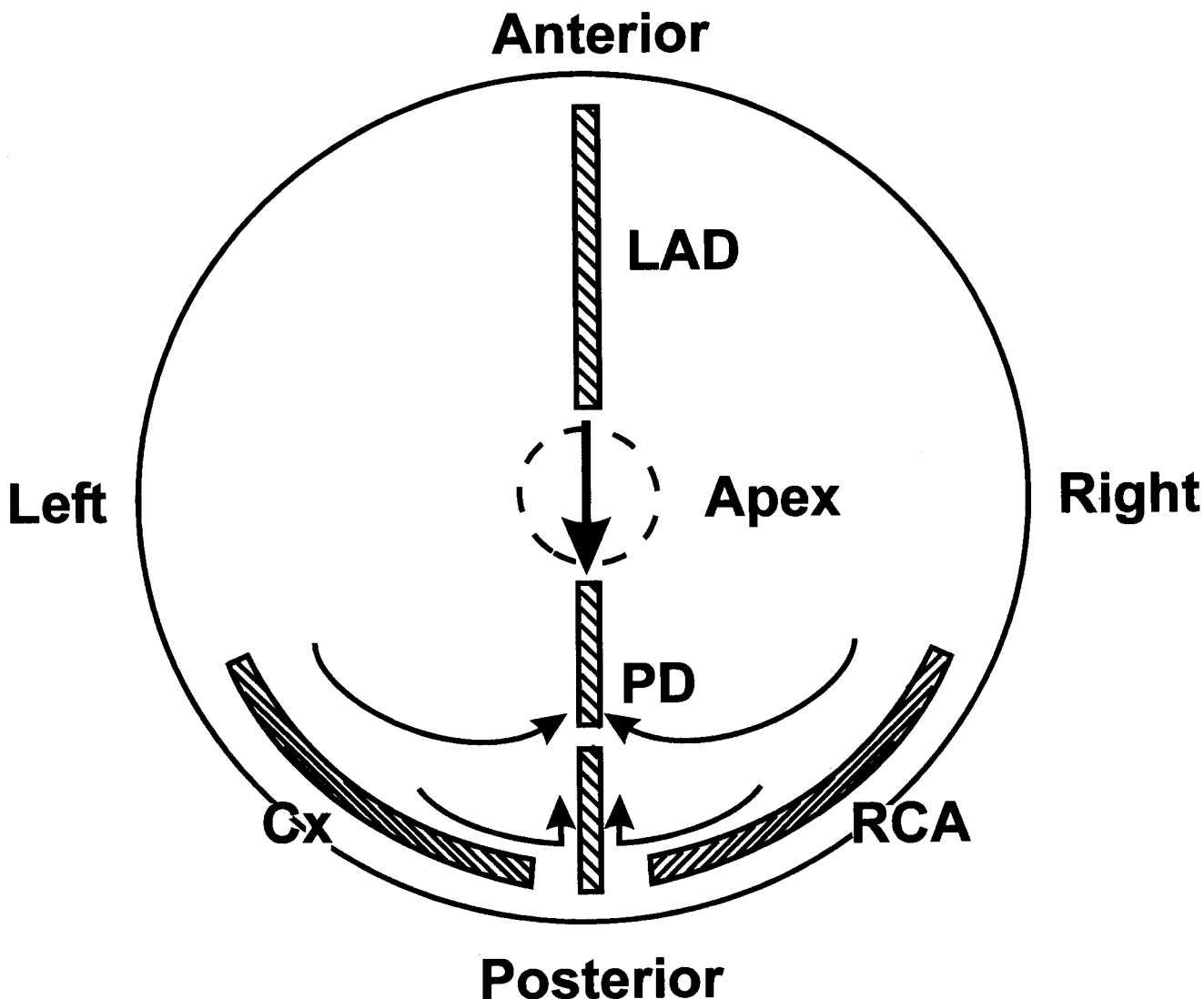
FIGURE 4.18. Schematic representation of the cardiac surface from an apical viewpoint, showing the possible alternative sources of the posterior descending artery (PD). This vessel may be a single trunk that originates from the circumflex artery (Cx), the RCA, or the LAD. The posterior descending artery may also be split into two segments with separate originations from the mid or distal RCA, the mid or distal circumflex artery, or the LAD.

acquired obstructive disease, however, functional testing (especially myocardial scintigraphic stress testing) will consistently rule out a diminished coronary reserve.[433] These coronary patterns become clinically relevant during surgical revascularization of the LAD territory, when the surgeon should be aware of the unusual anatomy.

(See Case Reports 4.35, 4.40, and 4.41 in the Atlas of Case Reports)

Ectopic Origination of the First Septal Branch

The first septal branch is commonly the largest (longest) septal vessel,[100] both because it provides for the uppermost portion of the ventricular septum (which has the largest di-

ameter in comparison to the other segments closer to the apex) and because it frequently has richer ramifications, which could reach even the atrioventricular node. This large vessel is occasionally seen to originate ectopically[296,311,403] from the following:

• The right anterior cusp
• The RCA
• The left coronary cusp[295]
• The left main trunk
• The first diagonal branch
• The proximal circumflex artery
• An anomalous RCA, LAD, LCA, or mixed trunk with an intraseptal course

ANOMALIES OF TERMINATION: CORONARY FISTULAS

As the coronary artery tree branches and propagates peripherally, it undergoes continuous tapering until it reaches the arteriolar level (the last segment of the coronary circulation to have a tunica media). The arterioles eventually drain into the capillary network, and only occasionally do they maintain small communications with sinusoidal intratrabecular spaces. *A sizable communication between a coronary artery and (1) a cardiac cavity or (2) any segment of the systemic or pulmonary circulation is generally called a coronary fistula.*[377] Any structure with a pressure lower than that of the systemic aorta (i.e., equal to the proximal coronary pressure) can drain blood flow from a coronary artery if an abnormal communication occurs, allowing fistulous flow. In reviewing the anatomic literature, starting with the historic early reports of Vieussens (1706) and Thebesius (1708), Baroldi and Scomazzoni[508] analyzed recurrent, lively discussions[525] that have occurred over the centuries about coronaro-cameral communications in the normal heart. These authors concluded that two types of communications normally exist in the human heart, as alternatives to normal drainage into the coronary veins/coronary sinus system:

1. Communications originating at the arteriolar level are established indirectly by means of *arterio-sinusoidal vessels* (which are irregularly shaped, measure 50 to 250 μm in diameter, lack a tunica media, and drain into any cardiac cavity), or directly by means of *arterioluminal vessels* (which are 40 to 200 μm in diameter, have a thin media, and drain into any cardiac cavity).

2. Venous communications or thebesian veins (first described by Thebesius [1686–1732], who injected various substances into the coronary sinus) are direct communications between a coronary vein and a cardiac cavity. They are especially common in the right atrium (where they measure up to 2 mm in size) and in the right ventricle.

The exact nature of these small coronaro-cameral connections remains unclear. However, they should probably not be called fistulas, because they do not involve substantial fistulous flow.

Angiographically, it is usually impossible to visualize the smaller coronary artery to cardiac cavity communications without the use of wedge injections.[128] Baroldi and Scomazzoni found such communications in almost all specimens by injecting the coronary arteries with latex or neoprene, which is fluid at room temperature but solidifies at 40 to 50 °C. The injections were made at 200 mm Hg of continuous pressure and were followed by further manual compression to enhance fluid progression during the 5- to 10-minute preparation period. To visualize veno-cameral communications, these investigators injected the coronary sinus with the same plastic material (of a different color), at 70 mm Hg of pressure, a few minutes after the beginning of the arterial injec-

tions. Appearance of the plastic gel in a cardiac cavity was considered evidence of an arterio- or veno-cameral communication. An important but unproved condition for accurately establishing this diagnosis was that the plastic gel not get past the capillary level. Using these techniques, Baroldi and Scomazzoni[508] demonstrated 200-μ arterioluminal communications in 86% of the left ventricles and 50% of the right ventricles but not in the atria; they also demonstrated $\leq$2-mm veno-cameral communications in the left ventricle, right ventricle, and right atrium but almost never in the left atrium.

The relationship between these findings and angiographic observations or functional status is not immediately clear. During angiography, only arterial injections are made, and any communication with a cardiac cavity is visualized at the end of contrast runoff. Clinically, however, it is impossible to know whether the capillary bed is or is not perfused by "fistulous" blood, which would differentiate potentially damaging (arterio-cameral) communications from benign (veno-cameral) ones.

Only during RCA injections (especially when performed subselectively and under high pressure) is contrast material frequently observed to drain into the anterior right ventricle and the right atrium.[128] This finding is not to be confused with the presence of thebesian veins. It merely shows that coronary veins of the right atrium and ventricle often drain directly into these cavities, without communicating with the coronary sinus.

Most likely, what appear as coronaro-cameral communications on angiography correspond to the >200-μ anatomic channels seen by Baroldi and Scomazzoni in normal hearts. Nevertheless, these channels should be subjected to specific studies, using proper techniques. The definition of coronaro-cameral fistulas is clear when larger vessels are involved, but it is not totally clear when smaller, multiple vessels are involved.[56,170,343] Small angiographic fistulas tend to occur only occasionally in patchy aggregates, affecting the smaller ramifications of several adjoining coronary branches or arteries, and typically involving the apical portions of both the left and right ventricles but never the outflow tracts. In such instances, the flow pattern indicates the presence of multiple small communications with limited flow, which is generally only diastolic into the left ventricle but systolo-diastolic into the right ventricle.[56,170] These communications do not cause ectasia of the proximal feeding arteries, nor do they tend to enlarge with time.[291]

This subject is being discussed extensively herein because of widespread persistent ignorance about the exact nature of the smaller communications between coronary vessels and cardiac cavities.[332] The overwhelming current tendency in the literature and in practice is to group these entities under the general heading of coronary fistulas and to imply that nutrient blood is shunted away from the myocardium.[111] Numerous reports have been published regarding patients with angina, ischemia, myocardial infarction, or arrhythmias in the presence of multiple small, patchy coronaro-cameral communications. However, overwhelming evidence (based

mainly on nuclear myocardial imaging data[342]) strongly suggests that these small communications are benign abnormalities that have no functional or prognostic consequences. Drainage of a coronary vein into the right ventricle or atrium is not only clinically irrelevant but normal. Both of these conditions are indeed coronaro-cameral communications, but they should not be confused with large coronaro-cameral fistulas, which are discussed later in this chapter.

Because of the widespread use of right ventricular biopsy techniques, cut arterial vessels are sometimes observed on angiograms, especially in patients subjected to repeated biopsies, as after heart transplantation.[220,343] This angiographic finding correlates with the inclusion of a sizable arterial segment in the biopsy specimen. Most such small communications eventually disappear with time, and we know of no reports of clinical consequences such as progressive enlargement of a fistula.

Another common entity that may be confused with a coronary fistula is a coronaro-cameral communication at the site of a large myocardial infarction, which is typically complicated by an organized mural clot.[448] The communication involves a ruptured artery or (more likely) vein, affecting either the native circulation in the necrotic area or neovessels grown into the myocardial scar or mural clot. Like small coronaro-cameral connections, these communications should be differentiated from congenital coronary fistulas.[343]

In conclusion, we propose that the term coronary fistula be used to identify only some of the many[313] normal or abnormal communications that can exist between a coronary vessel and a cardiac cavity or some other vessel; *the smaller, anatomic but not functional, communications should be called "coronaro-cameral micro-communications."* In contrast, a *functional coronary fistula* is characterized by at least one of the following features: (1) definite signs of fistulous flow (for instance, the affected feeding vessel will have a luminal diameter at least 50% greater than the "expected" diameter); (2) angiographically clear and prompt visualization of the receiving cardiovascular structure, where a step-up in the concentration of oxygen (or any other injected substance) should be apparent; (3) evidence of volume overload in the affected cardiac chambers;[118] and (4) evidence of steal (or ischemia) involving the myocardial nutrient blood flow,[269,369,524] ideally during segmental (nuclear) testing of the coronary reserve.[154,270]

The physiologic mechanisms that may lead to coronary steal in fistulas are essentially related to a diastolic pressure drop caused by fistulous runoff into a low-pressure cavity (*see Case Report 4.42 in the Atlas of Case Reports*). Whereas normally the aortic pressure is only mildly decreased (as in mild aortic insufficiency), the intracoronary pressure in the fistulous artery may undergo progressive diminution, especially during diastole, if the fistulous flow is large. Essentially, it is the balance between the inflow (coronary, ostial size) and the outflow (fistulous versus nutrient) that determines whether the absolute nutrient coronary flow is adequate or deficient. Multiple factors may af-

fect this balance, depending on the physiologic state and morphologic variant involved. For example, physical exercise tends to lower intramyocardial arteriolar resistance and increase the pressure in the systemic venous cavities (the usual recipients of coronary fistulous flow), inducing a favorable shift in the balance between nutrient and fistulous flow. Whereas distal coronary obstructive changes at the fistulous runoff site favorably affect coronary nutrient flow, proximal obstructive changes in the involved coronary artery or in the purely nutrient distal branches unfavorably affect such flow. Systemic hypertension is usually well tolerated, but hypotension of any etiology can be expected to have a critical adverse effect on the balance between nutrient and fistulous flow.

Traditionally, steal has been considered to be heralded by angina, electrocardiographic ischemic ST-T changes (at rest or during exercise), myocardial infarction, or arrhythmia. In trying to quantify the amount of stolen flow, some authors have directed their attention to the ratio between the fistulous flow and proximal flow in the affected nutrient artery.[264] This ratio can indeed establish the relative amount of steal (the percentage of proximal coronary flow that drains into the fistula) or the absolute amount of fistulous flow. Nevertheless, it does not prove the existence of a metabolically relevant steal phenomenon, based on the needs of the dependent myocardium at rest and under maximal functional demand conditions. The diagnosis of a steal phenomenon can be firmly established only by myocardial scintigraphy, which measures relative or absolute markers of myocardial ischemia in the affected area, both at rest and during evaluation of the coronary functional reserve.

The possibility that fistulous communications can indeed steal essential blood flow intended for the competing dependent myocardial vascular bed may be related to decreased driving pressure at the entry into the nutrient coronary branches. Acquired obstruction of the ostia of nutrient branches arising from the aneursymatic main artery is probably common in older patients (*see Case Report 4.42 in the Atlas of Case Reports*). It is not yet clear whether exercise or pharmacologic vasodilating agents can transiently change the pressure-flow-resistance values in cases of coronary fistulas; the expectation is that coronary arteriolar resistance will drop but that the fistulous opening cannot change.

Because functional coronaro-cameral fistulas,[88] as defined above, can carry large volumes of blood[523] (typically 1200 to 1500 mL/min or 20 to 25 mL/sec), use of a large-lumened angiographic catheter and a mechanical injector is necessary for adequate visualization of the involved vessels. Indeed, the angiographer should not be limited to the qualitative diagnosis of a coronary fistula and its receiving chamber or vessel[15,78,190,284,320,381,415] but should also aim for complete visualization of the nutrient myocardial branches. These vessels need special protection during interventional therapeutic procedures, whether surgical or catheter-mediated. In fact, the primary objective of any intervention in such cases should be to preserve, and possibly enhance,

nutrient myocardial flow, rather than simply to eliminate the fistulous tract. The absence of nutrient coronary branches arising from a fistulous tract should suggest an alternative diagnosis, namely ruptured aneurysm of an aortic sinus.[447] With the larger fistulas, a large quantity of contrast medium should be injected (about 20 mL/sec for at least 2 seconds), and the fistula should be examined in different projections, depending on its specific anatomy. It is prudent to avoid small-lumened catheters with only end holes (coronary pre-formed catheters) with high injection pressure and to use large-lumened catheters with side holes (like an NIH® or a Gensini® angiographic catheter). Alternatively, one may use a coronary angioplasty guiding catheter (large-lumened), kept in position by a 0.014-inch guidewire.

The proximal tract of a fistulous coronary artery should be regarded as an atypical example of a "mixed trunk" rather than as a simple coronary artery (which is defined as a vessel that provides exclusively nutrient flow).

Over the years, torrential flow will induce clinically important morphologic changes in the walls of a fistulous coronary artery. The fistulous tract—but not the distal, exclusively nutrient branches—will undergo progressive changes that range from simple dilation (as would be expected because of the increased blood flow) to frank aneurysm formation[18,126,262,288,382,522] (recognizable only because dilation is greater than in the adjacent vessel), intimal ulceration, medial degeneration, intimal rupture, atherosclerotic deposition, calcification,[288] side branch (nutrient) obstruction,[434] and mural thrombosis.[45,434,442] The ultimate, dreaded but rare, complication of the increased wall stress is coronary rupture into adjacent cardiac structures[61] or the pericardium.[156] Because the vessel wall's reaction to the prolonged increased flow is so variable, the observer should be cautious in estimating the amount of fistulous flow on the basis of luminal diameter alone. Vessel size, in itself, may be a fallacious parameter: in the most extreme case, a very large, aneurysmatic fistula could eventually become thrombosed, totally obliterating fistulous runoff to the distal vessel.[118,150,249,364]

In indicating whether intervention is necessary,[399] the amount of dilation of a fistulous vessel has recently become more relevant[52,118,333] than the amount of fistulous flow or symptoms and/or signs of myocardial ischemia.[114,389] Catheter-based[269] or surgical[63] intervention at an early age is generally recommended for patients with large fistulas, because of the risk of rupture and mural clotting[434,442]; moreover, aortic sinus disruption caused by an extremely enlarged coronary ostium can result in aortic insufficiency. Late atherosclerotic and thrombotic changes[218] will evolve even after total obliteration of the fistula. With respect to the optimal timing of surgery, another major consideration should be that reversibility of the ectasia is consistently reported only after surgical correction of fistulas in pediatric cases[118] and is never observed in older patients.[52] Because of these factors, many authorities have concluded that, once a large coronary fistula has been diagnosed, the optimal time for correction

is during the patient's fifth to fifteenth year of life; the timing of surgery in such cases should not be based on the time of onset of symptoms, the absolute amount of fistulous flow,[389] or signs of congestive failure or myocardial ischemia during stress testing. If the diagnosis is missed in the 5- to 15-year age range (as it frequently is), the indications for, and timing of, intervention may change because of variance of the risk-benefit ratio.[406] Older patients[445,495] may still do very well at surgery but may have more frequent complications (especially peri- and postoperative myocardial ischemic events[303,311,533] and extracardiac complications); moreover, after normalization of blood flow, their remaining risk of coronary thromboembolic disease in the excessively ectatic coronary segments will at least equal that of patients treated medically.[533] The recent introduction of catheter devices for the obliteration of coronary fistulas[87,161,217,303,314,315,368,402,441] will be further discussed in Chapter 5.

Concomitant obstructive coronary disease, in either the affected vessel or an unaffected one, may be the most common reason for clinical recognition of a coronary fistula and for surgical intervention in older patients.

Fistulous coronary connections usually involve structures that adjoin the coronary arteries, such as the coronary veins and the four cardiac cavities.[118,237,338,381,406,435,443,444] Less frequently, in otherwise normal hearts, a coronary fistula will drain into an extracardiac structure such as the pulmonary artery or its main branches or the superior vena cava.[18,466] Coronary-to-main pulmonary artery fistulas are usually small, multiple,[16] and of no clinical significance. Congenital coronary-pulmonary connections are sometimes seen in the context of other congenital heart defects, especially critical pulmonary valve stenosis or atresia or (even more frequently) pulmonary branch stenosis or atresia, or coarctation of the aorta.

Although the literature contains frequent references to "coronary-to-bronchial artery fistulas,"[17,41,144,171,347,366,373] we doubt the existence of such an entity. Both of these arteries are, in fact, systemic in patients with a normal cardiovascular anatomy, and fistulous flow cannot be expected to occur between two vascular sites that have identical pressure regimens. Communications have indeed been observed with special frequency between a coronary artery and a lung segment with a chronic infection[1] (bronchiectasia, sequestration, or pseudosequestration); in these cases, the involved vessels behaved more like neovascularizations or collaterals[220,349] than like fistulas.[17,173] Only occasional reporters have suggested that a "coronary to bronchial anastomosis" exists and can cause a myocardial infarction.[17,279] In congenitally sequestered pulmonary lobes, the systemic arterial supply is usually derived from the descending or abdominal aorta; in pseudosequestered lobes, however, it may originate from intercostal, mediastinal, subclavian, and pericardial arteries,[17,173,243,279] which probably connect with pulmonary arterial branches,[20] not bronchial ones.

Coronary-to-pulmonary communications may also appear after cardiac surgery, even heart transplantation (see Case

Report 4.44 in the Atlas of Case Reports). In these cases, the communication is not congenital, and the so-called fistulous artery consistently drains into a left lower pulmonary branch. Most of these connections develop after some degree of post-operative pleuropericarditis (and/or pulmonary atelectasis) has occurred; the inflammatory process must cause the formation of neovessels, which may connect with the lower-pressure pulmonary circulation via the subpleural plexus. Again, these neocommunications have no fistulous flow and are not connected with bronchial arteries or veins but only with pulmonary arteries (curiously, but probably because of a specific tropism, they are never connected with pulmonary veins).

For a more clinical discussion of coronary fistulas in pediatric patients, see Chapter 5.

(See Case Reports 4.43 through 4.49 in the Atlas of Case Reports)

COLLATERAL CORONARY ARTERIES: NORMAL VERSUS ANOMALOUS

"Anastomotic[508] or collateral coronary arteries" is a term that should be used to identify arterial sources other than normal, primary coronary vessels. Generally, collateral arteries are believed to develop after a coronary occlusion,[221] but detailed anatomic studies have shown that collaterals measuring less than 1 mm in luminal diameter (mostly about 0.3 mm[508] and provided with a thin media and endothelium), are extremely common in the normal human heart. Anatomically, these vessels connect either different, contiguous branches of the same artery or contiguous branches of opposite (right and left) coronary arteries. Because the number of collateral vessels in human hearts is quite high, coronary branches should not generally be considered "terminal" in anatomic terms. Functionally, however, most anastomotic circles are inactive and not visualized on coronary angiograms. In the acute stage of coronary occlusion with clinical myocardial infarction, collateral circulation is usually absent both physiologically and angiographically. Only in the subacute and chronic stages of coronary occlusion do collateral vessels become consistently apparent on angiographic studies. The origins of such collaterals are both homolateral and contralateral.

Typically, congenital "anomalous collaterals"[55] are >1-mm anastomotic communications between adjacent, unobstructed coronary arteries or branches. It is conceivable that these collaterals represent an unusual congenital pattern, but it is frequently impossible to rule out a previous transient coronary occlusion. In healthy individuals, normal (angiographically invisible) collaterals probably tend to be closed as a result of an absence of flow between arteries with the same pressure regimens; after a coronary occlusion, however, these collaterals may slowly open and enlarge as a result of the onset of a pressure gradient (this process is known as collateral recruitment). Flow-mediated vasodilation may be the mechanism of progressive enlargement of

anastomotic circles, as in coronary fistulas or ALCAPA (see Fig. CR4.11). When a coronary occlusion (usually involving thrombosis) resolves either spontaneously or because of intervention late after the development of large collaterals, these vessels can frequently still be visualized on coronary angiograms, where they may appear as "anomalous or inappropriate" collaterals. "Anomalous collateralization," a rare condition, tends to occur between the distal branches of the circumflex artery and RCA at the posterior atrioventricular groove.[55]

With respect to functional and prognostic implications, the only effect of anomalous collaterals (measuring >1 mm in luminal diameter, in the absence of coronary occlusion) would be protective, in the event that one of the connected coronary vessels became occluded.[55] Indeed, one postulated mechanism of preconditioning of the ischemic myocardium involves the development of intercoronary anastomotic circles during episodes of reversible ischemia; such collaterization would precede the final occlusive event and diminish its ischemic consequences.

In the absence of coronary occlusions, the largest collaterals are seen in cases of anomalous origination of a coronary artery from the pulmonary artery. In such cases, the collaterals are normal and appropriate, as they are governed by hemodynamic gradients established between the ectopic vessel and a normally originating coronary artery (see page 48).

PATHOPHYSIOLOGIC MECHANISMS AND CLINICAL IMPLICATIONS OF CORONARY ANOMALIES

This section summarizes the possible mechanisms by which coronary anomalies may produce clinical consequences. It also proposes a scheme for classifying coronary anomalies according to the involved pathophysiologic mechanism(s). First, however, it presents a brief summary of basic coronary physiology, based on Gould's excellent recent review,[145] to which interested readers are directed for a more in-depth discussion of this subject.

Overview of Normal Coronary Physiology

The primary source of energy for the resting, working heart is the oxidative metabolism of free fatty acids, which normally supplies 70 to 90% of the myocardial oxygen demand. At rest, the oxygen requirement of the myocardium is much greater (8 to 10 mL/min/100 g) than that of skeletal muscle (0.115 mL/min/100 g). Grossly, 20% of the myocardial oxygen requirement is dedicated to the basal metabolism (in the unloaded heart), and 1% is devoted to electrical activity. Volume work (15%) demands less energy than pressure work (64%). With exercise or an increased pressure workload, the oxygen demand is increased: a 50% increase in

myocardial contractility, pressure work, or the heart rate causes almost a 50% increase in the oxygen demand. During exercise, the maximal workload is 3 to 4.5 times greater than at rest; normally, this increased workload results in coronary flow that is 3 to 4.5 times greater than baseline flow.

The oxygen content of systemic arteries is about 80 vol%, whereas that of systemic and coronary veins is 60 vol% and 5 vol%, respectively. This finding reflects the unusually high amount of oxygen extracted by the myocardium under basal conditions (extraction being submaximal at rest).

The myocardial capillary density is about $3500/mm^2$ (compared with $400/mm^2$ in the skeletal muscles); 50 to 70% of the left ventricular myocardial capillaries are patent at rest, and essentially 100% are recruited during maximal workload conditions.

The capillaries have a diameter of about 3 μ during systole and 4 μ during diastole, evidencing the normal phasic increase in intramural pressure. The intercapillary distance is about 17 μ at rest, versus 11 to 14 μ during maximal capillary recruitment. A normal adult myocardial cell has a transverse diameter of about 18 μ (versus 50 μ for adult skeletal muscle cells), but hypertrophic myocytes can increase that diameter to 30 μ. Therefore, the surface for metabolic exchanges is about 15 times larger in normal myocardial cells than in skeletal fibers.

Compared with the subepicardium, the subendocardium normally has a similar basal flow rate but an increased wall stress, intramural systolic pressure, and oxygen demand; it also has a decreased maximal flow rate (coronary reserve), tissue oxygen concentration at rest, and venous oxygen saturation.

The major regulators of coronary blood flow are (1) the intramural pressure, (2) the aortic (coronary) pressure, which has an elective dependence on the diastolic mean pressure and time (as about 85% of the coronary blood flow occurs during diastole under basal conditions), (3) the myocardial metabolic rate, (4) the parasympathetic and sympathetic nerves, (5) endothelial function (autocrine), and (6) blood viscosity, which is greatly increased in polycythemia.

Coronary stenosis does not affect the resting blood flow until more than 90% of the luminal diameter becomes compromised. The coronary reserve (maximal vasodilatory capacity) is normal in the presence of 0 to 60% luminal narrowing, but it progressively decreases to 0% when the degree of stenosis approaches 90%. In the coronary circulation, vascular resistance is the sum of the proximal (subepicardial) and distal (arteriolar) resistance. Proximal resistance is negligible for proximal stenoses of up to 80 to 90%, but it becomes severe for stenoses of more than 90%. Endogenous vasodilators (especially nitrous oxide) and pharmacologic vasodilators will electively affect distal arteriolar resistance in the absence of significant ($\geq$90%) proximal stenosis. With stenoses greater than 90%, the peripheral vasodilating reserve is lost.

Under baseline conditions, the coronary system is subject to a "low-flow/high-resistance" state. In contrast, exercise or coronary vasodilator (adenosine or dipyridamole) stress/testing results in a "high-flow/low-resistance" state, in which a proximal coronary stenosis becomes more evident. Recent investigations[509–512] have suggested that the coronary tree has a dual mechanism of vasodilation: endothelium-dependent vasodilation of coronary vessels measuring >200 μm in diameter and nonendothelium-dependent vasodilation of arteriolae measuring <150–200 μm in diameter. Nitroglycerin acts by means of the first type of mechanism,[122] which essentially affects only the proximal, epicardial coronary arterial tone (capacitance vessels), where it is converted into its active form (nitric oxide) by the endothelium.[199] In contrast, adenosine directly stimulates smooth-muscle-cell A_2 receptors in arterioles (resistance vessels), without affecting capacitance vessels. Papaverine seems to affect both capacitance and resistance vessels. Myocardial perfusion imaging for determining coronary functional reserve is essentially based on these physiologic parameters.

A coronary anomaly may produce physiologic dysfunction or clinical consequences under the circumstances listed in Table 4.6, as discussed in the literature[70,72,238,327] and summarized in the following sections.

TYPES OF PATHOPHYSIOLOGIC MECHANISMS AND/OR CLINICAL IMPLICATIONS

This section discusses mechanisms reported to be involved in causing clinical manifestations or changes in the clinical outlook for patients with congenital coronary anomalies. The clinical relevance of coronary anomalies has recently been recognized by the American Heart Association, the American College of Cardiology, and the American Academy of Pediatrics.[534] The fact that 24% of sudden deaths in athletes can be related to coronary anomalies[534] underscores the importance of this subject.

Misdiagnosis of the Coronary Anatomy

Unusual coronary anatomic patterns may be confusing and easily misdiagnosed.[95,185] Misdiagnosis may adversely affect the treatment strategy and outcome, as well as the patient's psychosocial status and insurability. The following conditions may be particularly hard to recognize and/or interpret.

(Pseudo) Absence of a Coronary Artery

Labeling a coronary artery that is not visualized directly or by means of collateral, retrograde circulation as "absent," "occluded," or "missing" is usually erroneous in the absence of an acute myocardial infarction. Further studies, including ascending (and descending) aortography and selective subclavian or carotid angiography, with follow-through to the mediastinum (possibly using digital subtraction technology), should be performed in these cases.

TABLE 4.6. *Pathophysiologic mechanisms and coronary anomalies (functional classification)*

Pathophysiologic Mechanism	Coronary Anomaly	Certain	Possible	Unlikely
Misdiagnosis	Missing coronary artery	+		
	Hypoplastic coronary artery		+	
Myocardial ischemia, primary (fixed)	Absent coronary artery			+
	Hypoplastic coronary artery			+
	Ostial atresia	+		
	Ostial stenosis	+		
	Coronary fistula		+	
	ALCAPA	+		
	Muscular bridge			+
Myocardial ischemia, secondary (episodic)	Tangential origin		+	
	Ectopic origin (opposite sinus)		+	
	Myocardial bridge		+	
	Coronary ectasia		+	
	Coronary fistula		+	
	ALCAPA, neonatal	+		
	ALCAPA, adult		+	
Increased risk of fixed coronary atherosclerotic disease	Coronary fistula		+	
	ALCAPA	+		
	Coronary ectasia		+	
	Ectopic origin		+	
	Muscular bridge (proximal)		+	
Secondary aortic valve disease	Coronary aneurysm		+	
	Coronary fistula		+	
	ALCAPA		+	
Increased risk of bacterial endocarditis	Coronary fistula		+	
Ischemic cardiomyopathy (hibernation)	ALCAPA	+		
	Coronary fistula		+	
	Ectopic ostia		+	
Volume overload	Coronary fistula	+		
	ALCAPA	+		
Unusual technical difficulties during coronary angioplasty	Ectopic ostia	+		
	Split left coronary artery		+	
	Coronary fistula		+	
Complications during cardiac surgery	Ectopic ostia	+		
	Muscular bridge	+		

ALCAPA = anomalous origination of the left coronary artery from the pulmonary artery.

(Pseudo) Hypoplasia of a Coronary Artery

Most cases of so-called hypoplasia of a coronary artery actually involve alternative coronary branch patterns. True congenital coronary hypoplasia is probably a misdiagnosis, and the term should generally be avoided. Nevertheless, detailed angiographic studies should be performed to clarify the specific coronary distribution pattern for each myocardial segment. Only rarely during nuclear scintigraphic stress testing will the examiner find an association between a small coronary artery and reversible myocardial ischemia of the dependent myocardium that could strictly be classified as coronary hypoplasia (a doubtful congenital entity).

Myocardial Ischemia

Myocardial ischemia may result directly from coronary anomalies themselves (primary myocardial ischemic anomalies). Alternatively, it may be related to the fact that some coronary anomalies increase the probability of developing fixed obstructive disease (secondary myocardial ischemic anomalies) or transient ischemic events (secondary episodic myocardial ischemic anomalies).

The primary function of the coronary arteries is to provide metabolic myocardial perfusion. In dealing with coronary anomalies, clinicians are often frustrated by an unclear relationship between anatomy and function. This relationship is much more variable and subtle than in atherosclerotic obstructive coronary disease.[71,155,235,238,438,481,506]

Primary Myocardial Ischemia

Primary, or obligatory, myocardial ischemia is typically caused by obvious obstructive conditions such as congenital ostial stenosis or atresia, even in the presence of a rich collateral circulation. In these cases, myocardial perfusion testing is consistently positive for ischemia (fixed or reversible). By means of a different mechanism, primary myocardial

ischemia can also occur in anomalies like fistulas, which cause nutrient myocardial flow to compete with fistulous flow (in a lower-resistance circuit, organized in parallel) under conditions of limited supply, as in the case of a single, restrictive proximal coronary trunk. This phenomenon rarely occurs in the usual coronary fistula; it is more often associated with anomalous origination of a coronary artery from the pulmonary artery, in which the collateral circulation originating from the normal coronary arteries preferentially tends to drain blood into the ectopic coronary ostium in the pulmonary artery, while bypassing the myocardial bed.[80,206] The dramatic improvement in left ventricular function that is frequently seen after effective repair of this anomaly is clear evidence that a chronic hibernation state may exist well beyond infancy.[53,73,174,193,216,232,317,363] Despite earlier statements to the contrary in the literature, primary myocardial ischemia cannot be assumed to occur routinely because of an anomalous course alone,[83,300] specifically when a coronary artery courses between the pulmonary artery and the aorta.[335,476] The simplistic notion that such an anomalous course could be subject to an external scissors-like compression mechanism[44,58,151,200,383,410] is not generally sustainable in the light of current information. Indeed, these patients usually do not have reproducible angina or ischemia during stress testing, and they tend to live out their entire lives without any ischemic manifestation. Nevertheless, a few of them have ischemic events—usually sudden death,[65,108,188,236,250,261,383,385] a myocardial infarction,[261] or syncope—in the absence of coronary thrombosis or obvious stenosis.[58,110,208] Such patients may have a tangential slitlike ostium[272,322] or ostial ridges[472] or membranes,[66,319,409] but they rarely have a critical fixed stenosis.[213] At the present time, routine surgical correction (generally by means of bypass grafting) cannot be recommended on the basis of such anomalies alone; it would, however, be appropriate for survivors of sudden cardiac death or transient ischemia who have a positive provocation test. Despite exceptions widely reported in the literature, myocardial ischemia cannot usually be documented by stress testing, whether the patient has an isolated coronary intramyocardial course,[388] multiple coronaro-cameral micro-communications,[71,258,291] or coronary aneurysms or ectasia. If these conditions indeed lead to myocardial ischemia,[26] it is generally because of additional acquired features, as described in the following section.

Secondary, Episodic Myocardial Ischemia

Paradoxically, many coronary anomalies that, in fact, arise during the fetal period never produce clinical manifestations until many years later, if at all. One would expect that a congenital disease, especially a potentially lethal one, would not allow for normal life (as it frequently does, in the presence of negative stress tests), although it could suddenly cause a catastrophic event. In most cases, the congenital lesion by itself is not capable of causing the final event; rather, the congenital lesion increases the risk potential for

episodes of superimposed spasm,[265,266,338] intravascular clotting,[3,207,260,434,442,470] or accentuation of systolic narrowing in myocardial bridges, as brought about paradoxically by vasodilators.[74,246]

In recent years, the literature has included many case reports[25,26,208,272,298,384,395,411,502] that testify to the ischemic nature (in the dependent myocardial region) of adverse clinical events (myocardial infarction,[32,79,143,486] chest pain,[44] syncope,[461] ischemic cardiomyopathy,[461] or sudden death[58,79,240,241,453,461,469]) in patients with various coronary anomalies. Angiographic and autopsy studies[25,32,208,393] (carried out some variable time after the ischemic insult was substantially resolved, even if by death) have consistently failed to reveal the critical coronary obstructions or occlusions that would be expected in such cases. The implication is that a transient obstruction occurred, but this phenomenon could not be well documented. If such an obstruction can resolve that quickly, it must be caused by a coronary spasm in most cases. Platelet clot formation or full thrombosis is unlikely to be missed in angiographic or anatomic studies performed shortly after the event occurs.[3,384] Provocative testing designed to document coronary spastic potential must be more widely performed in clinical practice, to elucidate the pathophysiologic mechanism and prognosis, thereby facilitating rational therapeutic decision-making.[132,153,211] Spasm is probably involved in (1) most cases of ectopic coronary origination from the aorta, with tangential orientation of the proximal trunk and a slitlike orifice or ostial ridge[25,259,489] and (2) some muscular bridges (intramyocardial coronary arteries), especially the more extensive ones, in which long, thick myocardial bands cover a proximal main coronary trunk. It is likely, but not fully certain, that phasic bending of the intramyocardial coronary segment is a stimulus to spasm—even more than is systolic narrowing itself.[211,359] Provocative testing of endothelial dysfunction or excessive spasticity occasionally yield positive results.[132,153,211]

Conceivably, a coronary artery that originates from the opposite coronary sinus and courses between the aorta and the pulmonary artery could behave in a peculiar manner (previously unreported), especially during or after exercise or prolonged athletic training, leading to relevant clinical repercussions. We allude to stretching of the abnormal vessel against the aortic wall while that vessel is being subjected to the opposing forces of right and left ventricular dilation brought about by exercise. Indeed, during strenuous exercise, the cardiac output of young, trained athletes may increase to 25 to 30 L/min: under these circumstances, the dramatic increase in diastolic return flow to the ventricles is only partially compensated by an increased heart rate; a major increase in diastolic volume also results, which must be accompanied by important increases in aortic pressure and wall tension (both of which greatly exceed the respective pulmonary values) and also in right and left ventricular wall tension. By their nature and position, the coronary arteries (especially the LAD) are intrinsically anchored to the ventricular masses and may be subjected to unusual stretching
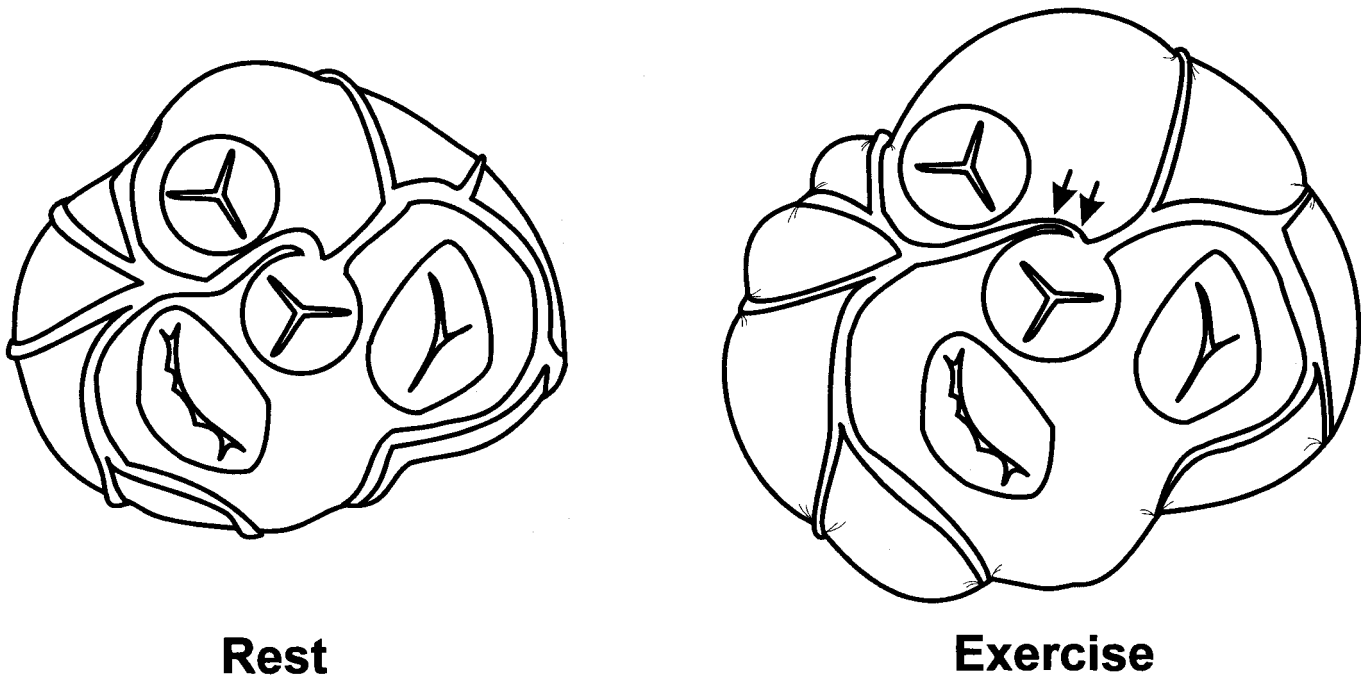
Rest

Exercise

FIGURE 4.19. Schematic representation of a possible mechanism of transient ischemia in patients with anomalous origin of the coronary artery from the opposite sinus. During exercise (right panel), physiologic cardiac enlargement may lead to stretching of the epicardial coronary arteries that are anchored to the myocardium, and compression of the proximal trunk against the aortic wall (arrows) may occur.

during exercise. If, on top of this physiologic condition, one superimposes an anomaly in which a coronary artery arises from the opposite side of the aorta and transverses the aorto-pulmonary septum adjacent to the aortic perimeter, compression of the anomalous coronary vessel by the aortic wall becomes likely (Fig. 4.19). Coronary compression might have two types of consequences: (1) direct diminution of coronary blood flow at a time of maximal demand and (2) coronary "mechanical stimulation" with a potential for secondary spasm (as when a coronary artery is mechanically stimulated by a catheter) or endothelial activation resulting in local platelet activation and/or autocrine vasomotor dysfunction. This abnormal physiologic state could persist during the immediate recovery period after strenuous exercise, when diastolic filling remains increased. Apparently, many of the sudden deaths reported to have been caused by such coronary anomalies occurred during the recovery phase after strenuous exercise.

Increased Risk of Fixed Coronary Atherosclerotic Disease

Some authors have suggested that fixed coronary atherosclerotic disease[77,113,215,294,430,473] could be a general consequence of the anomalous course of a coronary artery. However, recent studies,[435] including the angiographic analysis reported on pages 38–43, seem to indicate that most anomalous coronary vessels are not predisposed to early atheroscle-

rosis. The only certainty is that patients with congenital coronary anomalies have a much greater chance of being identified if they also have atherosclerotic coronary disease,[22] since coronary angiography is a most common diagnostic modality for ischemic heart disease.

In a recent study[528] designed to determine whether anomalies of coronary origin and course influence the location of atherosclerotic coronary disease, we documented no such influence. Indeed, in reviewing the Texas Heart Institute's database of 36,883 consecutive coronary angiograms, we encountered only 69 cases (0.2%) involving coronary anomalies of origination. Of this population, which was studied because of suspected coronary artery disease, 35 patients (51%) actually had such disease. Of the 105 proximal coronary arteries (LAD, RCA, and circumflex) studied in this subgroup of patients, 66 (63%) had a normal origin, and the other 39 (37%) were ectopic; obstructive disease was observed in 53% (35/66) of the normal segments and 30% (12/39) of the ectopic ones ($P = 0.027$).

The specific entity consisting of an ectopic, tangential ostium, maybe with a congenital fibrous ridge, may indeed increase the risk of additional ostial fixed, progressive obstructions,[75,260] probably because of unfavorable local rheologic factors. More studies are needed in this regard, including detailed anatomic analyses or adequate angiographic views of the anomalous ostia, accompanied by functional correlations. Highly atypical diffuse severe obstructive coronary disease has recently been documented in most cases

involving extreme overload of the right ventricle (pulmonary atresia with intact ventricular septum[129,142]) or the left ventricle (aortic valve atresia).[63] The obstructive lesions have been attributed to shrinkage and, even more, to fibrous intimal proliferation.[88,129] These lesions occur in the presence of high-velocity collateral flow, which vents the overloaded ventricular cavities. Surgical palliation of hemodynamic right ventricular overload may delay the progression of coronary pathology but also may eliminate critically important coronary collateral sources in the presence of severe proximal obstructions (see Chapter 6). Single coronary artery is not generically associated with an increased incidence of atherosclerosis; should atherosclerosis occur in the common trunk, however, the clinical consequences would be unusually severe, because the dependent myocardial territory includes the whole heart and no collateral circulation can develop.[262]

Secondary Aortic Valve Disease

In patients with coronary anomalies, clinically important aortic valve disease may result from (1) an independent congenital defect associated with coronary anomalies or (2) an acquired defect secondary to longstanding coronary anomalies, especially those involving greatly increased fistulous flow and enlarged coronary ostia—primarily coronary fistula and ectopic origination of the LCA from the pulmonary artery. As previously noted, when a coronary ostium attains a greatly enlarged diameter, the structure of the aortic cusp and the adjoining leaflet may be critically altered, resulting in aortic regurgitation. When a coronary artery originates ectopically from the pulmonary artery, it is the normal contralateral coronary artery (the source of collateral and fistulous flow) that may cause such impairment of the aortic valve.

Increased Risk of Bacterial Endocarditis

The earlier literature contains a few scattered reports concerning an increased risk of bacterial endocarditis or endoarteritis in patients with coronary anomalies, especially coronary fistulas. This risk is probably related more to coexisting aortic valve anomalies (even if their repercussions are initially minor) than to the coronary anomaly itself. The current extreme rarity of endocarditis[450] under such conditions may be caused by extensive use of antibiotics in the general population and routine prophylaxis for endocarditis in the presence of "heart murmurs," even in the absence of a definite diagnosis.

Cardiomyopathy

A cardiomyopathy is more likely to accompany ALCAPA or left coronary atresia than anomalous origination of the RCA, LAD, or circumflex artery (individually) from the pulmonary artery. As previously discussed, myocardial ischemic damage occurs prenatally in coronary atresia but neonatally in anomalous origination of a coronary artery from the pulmonary artery.

Some amazing observations have been widely confirmed in regard to the nature and behavior of chronic ischemia in pediatric patients with ALCAPA. Anatomically and histologically, this cardiomyopathy may involve cardiomegaly, left ventricular dilation, myocardial hypertrophy, secondary mitral insufficiency, changes associated with an acute myocardial infarction, and various degrees of interstitial, patchy, or diffuse fibrosis. After surgical correction of these anomalies, myocardial function may be recovered, often to an amazing extent. Not only are the results of nuclear myocardial perfusion studies dramatically improved or completely normalized but cardiomegaly, mitral regurgitation, and left ventricular systolic dysfunction may totally disappear.[454] In these cases, recovery is similar to that observed after revascularization of critical left main lesions but is consistently more extensive. This phenomenon clearly reflects the presence of a hibernating myocardium. Additionally, it is interesting to note that myocardial hypertrophy is a probable result of ischemia in young persons, and myocardial reabsorption (possibly by means of apoptosis) may occur after the chronic ischemia has been resolved.

Diffuse cardiomyopathy is also observed in some cases of anomalous origination of the LCA from the right anterior cusp. In such cases, ischemia is probably the original cause of the cardiomyopathy, but, as previously discussed, this event must be caused by clinical or subclinical episodic obstruction (spasm and/or clotting), followed by spontaneous revascularization.[461] In these cases, revascularization can prevent further worsening but may not produce a total recovery of myocardial function.

Volume Overload

A coronary fistula may cause cardiac enlargement and volume (diastolic) overload by creating significant shunting of blood through the fistula. Depending on the degree of fistulous flow and the size of the recipient cavity or vessel, different cardiac cavities will be affected to varying degrees. Coronary fistulas that drain into a systemic vein, coronary sinus, right-sided cardiac cavity, or pulmonary artery (including anomalous origination of a coronary artery from the pulmonary artery) will cause left-to-right shunting at systemic or near systemic pressures, resulting in volume overload (with cavitary dilation and an increased diastolic workload). Pulmonary hypertension is only rarely observed in cases involving coronary fistulas draining to the right ventricle or pulmonary artery, because the degree of shunting is never excessive[52] (i.e., greater than the systemic cardiac output or entailing a pulmonary-to-systemic flow ratio of >2:1). Volume overload may be poorly tolerated by patients who also have ischemia and/or a primary cardiomyopathy, as in ALCAPA.

Unusual Technical Difficulties During Coronary Angioplasty

Coronary anomalies of origin and course may increase the technical difficulty of coronary angioplasty for acquired or congenital obstructive disease.[27,62,67,392] Selective catheterization and guiding catheter support may be impaired, especially when a coronary artery originates tangentially and ectopically, outside the center of the aortic cusp.[60,436] In the absence of a left main coronary trunk, each individual left trunk (the LAD and circumflex artery) is smaller than normal, and the guiding catheter may easily become wedged.[391] A discussion of the adaptations needed during catheter interventions in these cases is beyond the scope of this book but is included elsewhere in the literature on interventional cardiology.[60,393,436]

(see Case Report 4.16 in the Atlas of Case Reports)

Complications During Cardiac Surgery

Ectopic coronary arteries may complicate the surgical treatment of associated cardiac conditions.[468] For instance, when an ectopic artery encircles or courses near the aortic or mitral valve annulus,[267] the artery may be injured during creation of the aortotomy or suture line at the time of aortic or mitral valve replacement.[267,328] During otherwise routine coronary artery bypass surgery, the surgeon may discover that the target coronary artery has an intramyocardial course. In such cases, the anomalous artery may not be found, or its unroofing may result in transmural perforation of the cardiac wall. Moreover, anomalous coronary branching patterns such as split RCA or LAD may confuse surgeons who are unfamiliar with them and may result in incomplete or erroneous bypass grafting.

REFERENCES *(in alphabetical order until #438)*

1. Abergel E, Aouate JM, Geslin J, et al. Dilatation des bronchs localisee. Etiologie meconnue de fistule coronaro bronchique. Arch Mal Coeur 1990;83:271.
2. Abrams HL, Barnhard HJ, Gruntzig AR, et al. Coronary arteriography. A practical approach. 1st ed. Boston: Little, Brown, 1983:10–72.
3. Agirbasli M, Martin GS, Stout JB, et al. Myocardial bridge as a cause of thrombus formation and myocardial infarction in a young athlete. Clin Cardiol 1997;20:1032.
4. Ahmad M, Merry SL, Haibach H. Evidence of impaired myocardial perfusion and abnormal left ventricular function during exercise in patients with isolated systolic narrowing of the left anterior descending coronary artery. Am J Cardiol 1981;48:832.
5. Akilli A, Kultursay H, Akin M, et al. Stenting of myocardial bridging. J Invasive Cardiol 1997;9:529.
6. Alam M. Brymer J, Smith S. Transesophageal echocardiographic diagnosis of anomalous left coronary artery from the right aortic sinus. Chest 1993;103:1617.
7. Allen GL, Snider TH. Myocardial infarction with a single coronary artery. Arch Intern Med 1966;117:261.
8. Alstrup P, Madsen T, Jagt T. Left coronary artery originating from the pulmonary artery: correction and total myocardial blood flow measurements. J Cardiovasc Surg (Torino) 1978;19:169.
9. Amplatz K, Anderson R. Angiographic appearance of myocardial bridging of the coronary artery. Invest Radiol 1968;3:213.

10. Angelini P, Leachman RD, Autrey A. Atypical phasic coronary narrowing. Cathet Cardiovasc Diagn 1986;12:39.
11. Angelini P, Trivellato M, Donis J, et al. Myocardial bridges: a review. Prog Cardiovasc Dis 1983;26:75.
12. Angelini P. Myocardial bridges revisited. Cathet Cardiovasc Diagn 1994;32:40.
13. Angelini P. The case of a fascinating dimple. Am J Cardiol 1993;72:102.
14. Anversa P, Sonnenblick EH. Ischemic cardiomyopathy: pathophysiologic mechanisms. Prog Cardiovasc Dis 1990;32:1.
15. Arani D, Greene D, Krocke F. Coronary artery fistulas emptying into the left heart chambers. Am Heart J 1978;96:438.
16. Ashraf SS, Shaukat N, Fisher M, et al. Bicoronary-pulmonary fistulae with coexistent mitral valve prolapse: a case report and literature review of coronary-pulmonary fistula. Eur Heart J 1994;15:571.
17. Aupetit JF, Gallet M, Boutarin J. Coronary-to-bronchial artery anastomosis complicated with myocardial infarction. Int J Cardiol 1988;18:93.
18. Aydogan U, Onursal E, Cantez T, et al. Giant congenital coronary artery fistula to left superior vena cava and right atrium with compression of left pulmonary vein simulating cor triatriatum—diagnostic value of magnetic resonance imaging. Eur J Cardiothorac Surg 1994;8:97.
19. Bahrati S, Lev M. The pathology of congenital heart disease. Armonk, NY: Futura Publishing, 1996.
20. Baim DS, Klinen H, Silverman JF. Bilateral coronary artery-pulmonary artery fistulas. Report of five cases and review of the literature. Circulation 1982; 65:810.
21. Baljepally RM, Pollock SH, Magram MY. Transluminal angioplasty of a single coronary artery anomaly during acute myocardial infarction—a case report. Angiology 1993;44:981.
21a. Baltaxe HA, Wixson D. The incidence of congenital anomalies of the coronary arteries in the adult population. Radiology 1977;122:47.
22. Barendra C, Chan CN, Tan A. Single coronary artery: a case report and review of current literature. Singapore Med J 1995;36:335.
23. Edwards WD. Applied anatomy of the heart. In Giuliani ER, Gersh BJ, McGoon MD, et al., eds: Mayo Clinic practice of cardiology. St. Louis: Mosby, 1996:474–481.
24. Barresi V, Susmano A, Colandrea MA, et al. Congenital absence of the circumflex coronary artery. Clinical and cineangiographic observations. Am Heart J 1973;86:811.
25. Barth CW, Roberts WC. Left main coronary artery originating from the right sinus of Valsalva and coursing between the aorta and pulmonary trunk. J Am Coll Cardiol 1986;7:366.
26. Bartorelli AL, Pepi M, Sganzerla P, et al. Syncope with cardiac arrest as the first manifestation of two congenital left coronary artery-to-main pulmonary artery fistulae. Am Heart J 1994;127:207.
27. Bass TA, Miller AB, Rubin MR, et al. Transluminal angioplasty of anomalous coronary arteries. Am Heart J 1986;112:610.
28. Becker AE, Anderson RH. Cardiac embryology: a help or a hindrance in understanding congenital heart disease? In: Nora JJ, Takao A, eds. Congenital heart disease: causes and processes. Mount Kisco, NY: Futura Publishing, 1984:339–351.
29. Becker AE. Congenital coronary arterial anomalies of clinical relevance. Cor Art Dis 1995;6:187.
30. Bedogni F, Castellani A, La Vecchia L, et al. Atresia of the left main coronary artery: clinical recognition and surgical treatment. Cathet Cardiovasc Diagn 1992;25:35.
31. Befeler B, Aranda JM, Embi A, et al. Coronary artery aneurysms: study of their etiology, clinical course and effect on the left ventricular function and prognosis. Am J Med 1977;62:597.
32. Benge W, Martins JB, Funk DC. Morbidity associated with anomalous origin of the right coronary artery from the left sinus of Valsalva. Am Heart J 1980;99:46.
33. Bennett JM, Blomerus P. Thallium-201 scintigraphy perfusion defect with dipyridamole in a patient with a myocardial bridge. Clin Cardiol 1988;11:268.
34. Bestetti RB, Costa RB, Oliveira JSM, et al. Congenital absence of the circumflex coronary artery associated with dilated cardiomyopathy. Int J Cardiol 1985;8:331.
35. Bestetti RB, Costa RS, Kazava DK, et al. Can isolated myocardial bridging of the left anterior descending coronary artery be associated with sudden death during exercise? Acta Cardiol 1991;46:27.
36. Bestetti RB, Costa RS, Zucolotto S, et al. Fatal outcome associated

with autopsy proven myocardial bridging of the left anterior descending coronary artery. Eur Heart J 1989;10:573.

37. Betriu A, Pare JC, Sanz GA, et al. Myocardial infarction with normal coronary arteries: a prospective clinical-angiographic study. Am J Cardiol 1981;48:28.

38. Bezerra AJC, Prates JC, DiDio LJA. Incidence and clinical significance of bridges of myocardium over the coronary arteries and their branches. Surg Radiol Anat 1987;9:273.

39. Binet JP, Guiraudon G, Langlois J, et al. Angine de poitrine et ponts musculaires sur l'arterie interventriculaire anterieure: a propos de trois cas operes. Arch Mal Coeur 1978;71:251.

40. Bittner V, Nath HP, Cohen M, et al. Dual connection of the left anterior descending coronary artery to the left and right coronary arteries. Cathet Cardiovasc Diagn 1989;16:168.

41. Bjork L. Angiographic demonstration of extracardial anastomoses to the coronary arteries. Radiology 1966;87:274.

42. Blake HA, Manion WC, Mattingly TW, et al. Coronary artery anomalies. Circulation 1964;30:927.

43. Bland EF, White PD, Garland J. Congenital anomalies of the coronary arteries. Am Heart J 1933;8:787.

44. Bloomfield P, Ehrlich C, Folland ED, et al. Anomalous right coronary artery: a surgically correctable cause of angina pectoris. Am J Cardiol 1983;51:1235.

45. Bolognesi R, Tsialtas D, Barbaresi F, et al. Single coronary artery-right ventricular fistula with a partially thrombosed large aneurysm of its proximal tract in a 66-year-old man. Eur Heart J 1994;15:1720.

46. Bove AA, Vlietstra RE. Spasm in ectatic coronary arteries. Mayo Clin Proc 1985;60:822.

47. Brandt B III, Martins JB, Marcus ML. Anomalous origin of the right coronary artery from the left sinus of Valsalva. N Engl J Med 1983;309:596.

48. Brandt PWT, Partridge JB, Wattie WJ. Coronary arteriography; method of presentation of the arteriogram report and a scoring system. Clin Radiol 1977;28:361.

49. Brooks H. Two cases of abnormal coronary artery of the heart arising from the pulmonary artery. With some remarks upon the effect of this anomaly in producing cirsoid dilatation of the vessels. J Anat Physiol 1884;20:26.

50. Burke AP, Farb A, Virmani R, et al. Sports-related and non–sports-related sudden cardiac death in young adults. Am Heart J 1991;121:568.

51. Byrum CJ, Blackman MS, Schneider B, et al. Congenital atresia of the left coronary ostium and hypoplasia of the left main coronary artery. Am Heart J 1980;99:354.

52. Carrel T, Tkebuchava T, Jenni R, et al. Congenital coronary fistulas in children and adults: diagnosis, surgical technique and results. Cardiology 1996;87:325.

53. Carvalho JS, Redington AN, Oldershaw PJ, et al. Analysis of left ventricular wall movement before and after reimplantation of anomalous left coronary artery in infancy. Br Heart J 1991;65:218.

54. Carvalho VB, Macruz R, Decourt LV, et al. Hemodynamic determination of coronary constriction in human myocardial bridges. Am Heart J 1984;108:73.

55. Celano C, Peters RW, Fisher ML. Coronary collateral blood flow in a patient with angiographically normal coronary arteries. Cathet Cardiovasc Diagn 1987;13:325.

56. Cha SD, Singer E, Maranhao V, et al. Silent coronary artery-left ventricular fistula: a disorder of the thebesian system. Angiology 1978;29:169.

57. Chaitman BR, Bourassa MG, Lesperance J, et al. Aberrant course of the left anterior descending coronary artery associated with anomalous left circumflex origin from the pulmonary artery. Circulation 1975;52:955.

58. Chaitman BR, Lesperance J, Saltiel J, et al. Clinical, angiographic, and hemodynamic findings in patients with anomalous origin of the coronary arteries. Circulation 1976;53:122.

59. Chambers JD Jr, Johns JP, Davees TS. Myocardial stunning resulting from systolic coronary artery compression by myocardial bridging. Am Heart J 1994;128:1036.

60. Chan CNS, Berland J, Cribier A, et al. Angioplasty of the right coronary artery with origin of all three coronary arteries from a single ostium in the right sinus of Valsalva. Am Heart J 1993;126:985.

61. Chapman RW, Watkins J. Rupture of right coronary artery aneurysm into the right atrium. Br Heart J 1978;40:938.

62. Charney R, Spindola-Franco H, Grose R. Coronary angioplasty of anomalous right coronary arteries. Cathet Cardiovasc Diagn 1993;29:233.

63. Cheatham JP, Ruyle NA, NcManus BM, et al. Origin of the right coronary artery from the descending thoracic aorta: angiographic diagnosis and unique coronary artery anatomy at autopsy. Cathet Cardiovasc Diagn 1987;13:321.

64. Chee TP, Jensen DP, Padnick MB, et al. Myocardial bridging of the left anterior descending coronary artery resulting in subendocardial infarction. Arch Intern Med 1981;141:1703.

65. Cheitlin MD, De Castro CM, McAllister HA. Sudden death as a complication of anomalous left coronary origin from the anterior sinus of Valsalva: a not-so-minor congenital anomaly. Circulation 1974;50:780.

66. Cheitlin MD. Congenital coronary artery anomalies: pathologic aspects. In: Virmani R, Forman MB, eds. Non-atherosclerotic ischemic heart disease. New York: Raven, 1989:81–98.

67. Chen H, Lo P, Wu C, et al. Coronary angioplasty of a single coronary artery with an anomalous origin in the ascending aorta. J Invas Cardiol 1997;9:188.

68. Chen JN, Liao R. A study of the myocardial bridges on the coronary arteries in the Chinese. Acta Anat Sinica 1965;8:106.

69. Chen YT, Hwang CL, Kan MN. Large, isolated, congenital aneurysm of the anterior descending coronary artery. Br Heart J 1993;70:274.

70. Cheng TO. Anomalous coronary arteries. Int J Cardiol 1993;40:183.

71. Cheng TO. Left coronary artery-to-left ventricular fistula: demonstration of coronary steal phenomenon. Am Heart J 1982;104:870.

72. Cheng TO. Prevalence and relevance of coronary artery anomalies. Cathet Cardiovasc Diagn 1997;42:276.

73. Cherian KM, Bharati S, Rao SG. Surgical correction of anomalous origin of the left coronary artery from the pulmonary artery. J Card Surg 1994;9:386.

74. Chopra PS, Reed WH, Wilson AD, et al. Delayed presentation of anomalous circumflex coronary artery arising from pulmonary artery following repair of aortopulmonary window in infancy. Chest 1994;106:1920.

75. Ciampricotti R, El Gamal M. Vasospastic coronary occlusion associated with a myocardial bridge. Cathet Cardiovasc Diagn 1988;14:118.

76. Cieslinski G, Rapprich B, Kober G. Coronary anomalies: incidence and importance. Clin Cardiol 1993;16:711.

77. Click RL, Holmes DR Jr, Vlietstra RE, et al. Anomalous coronary arteries: location, degree of atherosclerosis and effect on survival: a report from the Coronary Artery Surgery Study. J Am Coll Cardiol 1989;13:531.

78. Teno LA, Santos JL, Bestetti RB, et al. Congenital circumflex coronary artery fistula with drainage into the left ventricle. Tex Heart Inst J 1993;20:304.

79. Corrado D, Thiene G, Cocco P, et al. Non-atherosclerotic coronary artery disease and sudden death in the young. Br Heart J 1992;68:601.

80. Cowie MR, Mahmood S, Ell PJ. The diagnosis and assessment of an adult with anomalous origin of the left coronary artery from the pulmonary artery. Eur J Nucl Med 1994;21:1017.

81. Culbertson C, De Campli W, Williams R, et al. Congenital valvular aortic stenosis and abnormal origin of the right coronary artery: rare combination with important clinical implications. Pediatr Cardiol 1995;16:73.

82. Culham JAG. Abnormalities of the coronary arteries. In: Freedom RM, Mawson JB, Yoo SJ, Benson LN, eds. Congenital heart disease: textbook of angiocardiography. Armonk NY: Futura Publishing, 1997:849–867.

83. Dalal JJ, West RO, Parker JO. Isolated anomaly of the left anterior descending coronary artery. Cathet Cardiovasc Diagn 1984;10:189.

84. Daoud AS, Pankin D, Tulgan H, et al. Aneurysms of the coronary artery: report of ten cases and review of the literature. Am J Cardiol 1963;11:228.

85. Davidson PH, McCrackan BH, McIlveen JJS. Congenital coronary arteriovenous aneurysm. Br Heart J 1955;17:569.

86. Davis JS, Lie JT. Anomalous origin of a single coronary artery from the innominate artery. Angiology 1977;28:775.

87. De Feyter PJ, Wardeh R, Majid PA. Exercise-induced and variant form of angina pectoris in a patient with hypoplasia of the left coronary artery: clinical, metabolic and angiographic observations. Eur J Cardiol 1981;12:147.

88. De Nef JJ, Varghese PJ, Losekoot G. Congenital coronary artery fistula: report of 17 cases with a note on natural history of lesion. Br Heart J 1971;33:150.

89. De Wolf D, Terriere M, De Wilde P, Reidy JF. Embolization of a coronary fistula with a controlled delivery platinum coil in a 2-year-old. Pediatr Cardiol 1994;15:308.

90. de Zwaan C, Wellens HJ. Left ventricular aneurysm subsequent to cleavage of myocardial bridging of a coronary artery. J Am Coll Cardiol 1984;3:1345.

91. Dean JW, Mills PG. Abnormal ventricular repolarization in association with myocardial bridging. Br Heart J 1994;71:366.

92. Den Dulk K, Brugada P, Braat S, et al. Myocardial bridging as a cause of paroxysmal atrioventricular block. J Am Coll Cardiol 1983; 1:965.

93. Desseigne P, Tabib A, Loire R. Myocardial bridging on the left anterior descending coronary artery and sudden death: an autopsy study of 19 cases. Arch Mal Coeur 1991;84:511.

94. Dicicco BS, McManus BM, Waller BF, et al. Separate aortic ostium of the left anterior descending and left circumflex coronary arteries from the left aortic sinus of Valsalva (absent left main coronary artery). Am Heart J 1982;104:153.

95. Donaldson RM, Raphael MJ. Missing coronary artery: review of technical problems in coronary arteriography resulting from anatomical variants. Br Heart J 1982;47:62.

96. Donaldson RM, Raphael M, Radley-Smith R, et al. Angiographic identification of primary coronary anomalies causing impaired myocardial perfusion. Cathet Cardiovasc Diagn 1983;9:237.

97. Donaldson RM, Raphael MJ, Yacoub MH, et al. Hemodynamically significant anomalies of the coronary arteries. Thorac Cardiovasc Surg 1982;30:7.

98. Donaldson RM, Thornton A, Raphael MJ, et al. Anomalous origin of the left anterior descending coronary artery from the pulmonary trunk. Eur J Cardiol 1979;10:295.

99. Doorey AJ, Wills JS, Blasetto J, et al. Usefulness of magnetic resonance imaging for diagnosing an anomalous coronary artery coursing between aorta and pulmonary trunk. Am J Cardiol 1994;74:198.

100. Dorald BE, Essex HW. The coronary septal artery. An anatomic and electrocardiographic study. Am J Physiol 1954;176:143.

101. Dottori V, Torre F, Spagnolo S, et al. The intramyocardial coronary artery and the muscular bridge. The physiopathological and surgical considerations in a clinical case. G Ital Cardiol 1993;23:787.

102. Doty DB, Chandramouli B, Schieken RE, et al. Anomalous origin of the left coronary artery from the right pulmonary artery. J Thorac Cardiovasc Surg 1976;71:787.

103. Drexler H, Zeiher AM, Wollschlager, et al. Flow-dependent coronary artery dilation in humans. Circulation 1989;80:466.

104. Driscoll DJ, Nihill MR, Mullins CT, et al. Management of symptomatic infants with anomalous origin of the left coronary artery from the pulmonary artery. Am J Cardiol 1981;47:642.

105. Driscoll DJ. Congenital coronary artery anomalies. In: Garson A, Bricker TJ, McNamara DG, eds. The science and practice of pediatric cardiology. Philadelphia: Lea & Febiger, 1990:1453–1461.

106. Drory Y, Turetz Y, Hiss Y, et al. Sudden unexpected death in persons less than 40 years of age. Am J Cardiol 1991;68:1388.

107. Duerinckx AJ, Bogaert J, Jiang H, et al. Anomalous origin of the left coronary artery: diagnosis by coronary MR angiography. AJR 1995; 164:1095.

108. Duran AC, Angelini A, Frescura C, et al. Anomalous origin of the right coronary artery from the left aortic sinus and sudden infant death. Int J Cardiol 1994;45:147.

109. Ebert PA, Peter RH, Gunnells JC, et al. Resecting and grafting of coronary artery aneurysm. Circulation 1971;43:593.

110. Edelstein J, Juhasz RS. Myocardial infarction in the distribution of a patent anomalous left circumflex coronary artery. Cathet Cardiovasc Diagn 1984;10:171.

111. Edward JE. Anomalous coronary arteries with special reference to arteriovenous-like communications. Circulation 1958;17:1001.

112. Edwards JE, Burnsides C, Swarm RL, et al. Arteriosclerosis in the intramural and extramural portion of coronary arteries in the human heart. Circulation 1956;13:235.

113. Edwards JE. The direction of blood flow in coronary arteries arising from the pulmonary trunk (editorial). Circulation 1964;29:163.

114. Effler DB, Sheldon WC, Turner JJ, et al. Coronary arteriovenous fistulas: diagnosis and surgical management: report of 15 cases. Surgery 1967;61:41.

115. Engel HJ, Torres C, Page HL. Major variations in anatomical origin of the coronary arteries: angiographic observations in 4250 patients without associated congenital heart disease. Cathet Cardiovasc Diagn 1975;1:157.

116. Erbel R, Ge J, Rupprecht HJ, et al. Comparison of intravascular ultrasound and angiography in the assessment of myocardial bridging. Circulation 1994;89:1725.

117. Eugster GS, Oliva PB. Anomalous origin of the right coronary artery from the pulmonary artery. Chest 1973;63:294.

118. Farooki ZQ, Nowlen T, Hakimi M, et al. Congenital coronary artery fistulae: a review of 18 cases with special emphasis on spontaneous closure. Pediatr Cardiol 1993;14:208.

119. Faruqui AMA, Maloy WC, Felner JM, et al. Symptomatic myocardial bridging of coronary artery. Am J Cardiol 1978;41:1305.

120. Feld H, Guadanino V, Hololander G, et al. Exercise-induced ventricular tachycardia associated with a myocardial bridge. Chest 1991;99: 1295.

121. Feldman AM, Baughman KL. Myocardial infarction associated with a myocardial bridge. Am Heart J 1986;111:784.

122. Feldman RL, Pepine CJ, Conti CR. Magnitude of dilatation of large and small coronary arteries by nitroglycerin. Circulation 1981;64:324.

123. Fernandes F, Alam M, Smith S, et al. The role of transesophageal echocardiography in identifying anomalous coronary arteries. Circulation 1993;88:2532.

124. Ferreira AG Jr, Trotter SE, Konig B Jr, et al. Myocardial bridges: morphological and functional aspects. Br Heart J 1991;66:364.

125. Finley JP, Howman-Giles K, Gilday DL, et al. Thallium-201 myocardial imaging in anomalous left coronary artery arising from the pulmonary artery. Am J Cardiol 1978;42:675.

126. Floyd WL, Young WG, Johnsrude IS. Coronary arterial-left atrial fistula. Case with obstruction of the inferior vena cava by a giant left atrium. Am J Cardiol 1970;25:716.

127. Flynn MS, Kern MJ, Aguirre FV, et al. Intramyocardial muscle bridging of the coronary artery: An examination of a diastolic "spike and dome" pattern of coronary flow velocity. Cathet Cardiovasc Diagn 1994;32:36.

128. Freedom RM, Culham JAG, Moes CAF. Anomalies of the coronary arteries. In: Freedom RM, Culham JAG, Moes CAF, eds. Angiocardiography of congenital heart disease. New York: Macmillan, 1974: 405–421.

129. Freedom RM, Benson LN. The etiology of myocardial ischemia: surgical considerations. In: Freedom RM, ed. Pulmonary atresia with intact ventricular septum. New York: Futura, 1989:233.

130. Fu M, Hung JS, Yeh SJ, et al. Reversal of silent myocardial ischemia by surgery for isolated anomalous origin of the left anterior descending coronary artery from the pulmonary artery. Am Heart J 1992;124: 1369.

131. Gaither NS, Rogan KM, Stajduhar K, et al. Anomalous origin and course of coronary arteries in adults: identification and improved imaging utilizing transesophageal echocardiography. Am Heart J 1991; 122:69.

132. Gallet B, Adams C, Hlitgen M, et al. Myocardial bridge of the left anterior descending coronary artery and myocardial infarction: does coronary spasm play a part? Arch Mal Coeur Vaiss 1991;84:517.

133. Galli M, Politi A, Zerboni S. "Functional myocardial bridging" and "hyperkinetic state": a rare association as a cause of acute myocardial infarction. G Ital Cardiol 1997;27:1286.

134. Ge J, Erbel R, Meyer J, et al. Comparison of intravascular ultrasound and angiography in the assessment of myocardial bridging. Circulation 1994;89:1725.

135. Ge J, Jeremias A, Simon HU, et al. A new and characteristic coronary flow pattern in patients with myocardial bridging demonstrated by intracoronary FloWire. Circulation 1997;96:704.

136. Geiringer E. The mural coronary artery. Am Heart J 1951;41:359.

137. Gentzler RD, Gault JH, Liedtke AJ, et al. Congenital absence of the left circumflex artery in the systolic click syndrome. Circulation 1975; 52:490.

138. Ghahrani A, Iyengar R, Cunha D, et al. Myocardial infarction due to congenital coronary arterial aneurysm (with successful saphenous vein bypass graft). Am J Cardiol 1972;29:863.

139. Ghosh PK, Friedman M, Vidne BA. Isolated congenital atresia of the left main coronary artery and atherosclerosis. Ann Thorac Surg 1993; 55:1564.

140. Gibbs HH, Spokojny AM, Molloy TJ, et al. Percutaneous transluminal

coronary angioplasty of a right coronary artery arising from the left main coronary artery. Cathet Cardiovasc Diagn 1993;30:37.

141. Gibson R, Nihill MR, Mullins CE, et al. Congenital coronary artery obstruction associated with aortic valve anomalies in children: report of two cases. Circulation 1981;64:857.

142. Gittenberger-de Groot AC, Sauer U, Bindl L, et al. Competition of coronary arteries and ventriculo-coronary arterial communications in pulmonary atresia with intact ventricular septum. Int J Cardiol 1988; 18:243.

143. Glover MV, Kuber MT, Warren SE, et al. Myocardial infarction before age 36: risk factor and arteriographic analysis. Am J Cardiol 1982;49:1600.

144. Gobel FL, Anderson CF, Baltaxe HA, et al. Shunts between the coronary and pulmonary arteries with normal origin of the coronary arteries. Am J Cardiol 1970;25:655.

145. Gould KL: Coronary artery stenosis. New York: Elsevier Science Publishers, 1991:7–71.

146. Grant RT, Regnier M. The comparative anatomy of the cardiac coronary vessels. Heart 1926;13:285.

147. Green CE. Unusual coronary anatomy and variations. In: Green CE. Coronary cinematography. Philadelphia: Lippincott-Raven, 1996: 19–38.

148. Greenspan M, Iskandrian AS, Catherwood E, et al. Myocardial bridging of the left anterior descending artery: evaluation using exercise thallium-201 myocardial scintigraphy. Cathet Cardiovasc Diagn 1980; 6:173.

149. Grenadier E, Beyar R, Amikam S, et al. Two-vessel PTCA of single anomalous coronary artery. Am Heart J 1992;123:220.

150. Griffiths SP, Ellis K, Hardof AJ, et al. Spontaneous complete closure of a congenital coronary fistula. J Am Coll Cardiol 1983;2:1169.

151. Grollman JH Jr, Mao SS, Weinstein SR. Arteriographic demonstration of both kinking at the origin and compression between the great vessels of an anomalous right coronary artery arising in common with a left coronary artery from above the left sinus of Valsalva. Cathet Cardiovasc Diagn 1992;25:46.

152. Grondin P, Bourassa MB, Noble J, et al. Successful course after supra-arterial myotomy for myocardial bridging and milking effect of the left anterior descending artery. Ann Thorac Surg 1977;24:422.

153. Grover M, Mancini GB. Myocardial bridge associated with pacing-induced coronary spasm. Am Heart J 1984;108:1540.

154. Gupta NC, Beauvais J. Physiologic assessment of coronary artery fistula. Clin Nucl Med 1991;16:40.

155. Gutgesell HP, Pinsky WW, DePuey EG. Thallium-201 myocardial perfusion imaging in infants and children. Value in distinguishing anomalous left coronary artery from congestive cardiomyopathy. Circulation 1980;61:596.

156. Haberman JH, Howard ML, Johnson ES. Rupture of the coronary sinus with hemopericardium. A rare complication of coronary arteriovenous fistula. Circulation 1963;28:1143.

157. Hackett D, Hallidie-Smith KA. Spontaneous closure of coronary artery fistula. Br Heart J 1984;52:477.

158. Hansen BF. Myocardial covering on epicardial coronary arteries. Prevalence, localization, and significance. Scand J Thorac Cardiovasc Surg 1982;16:151.

159. Hanzlick R, Stivers RR. Sudden death in a marathon runner with origin of the right coronary artery from the left sinus of Valsalva (letter to editor). Am J Cardiol 1983;51:1467.

160. Harada K, Ito T, Suzuki Y, et al. Congenital atresia of left coronary ostium. Eur J Pediatr 1993;152:539.

161. Hartnell GG, Jordan SC. Balloon embolization of a coronary arterial fistula. Int J Cardiol 1990;29:381.

162. Hartnell GG, Parnell BM, Pridie RB. Coronary artery ectasia: its prevalence and clinical significance in 4,993 patients. Br Heart J 1985; 54:392.

163. Hausdorf G, Gravinghoff L, Keck EW. Effects of persisting myocardial sinusoids on left ventricular performance in pulmonary atresia with intact ventricular septum. Eur Heart J 1987;8:291.

164. Herreira AG Jr, Trotter SE, Koning B Jr, et al. Myocardial bridges: morphological and functional aspects. Br Heart J 1991;66:364.

165. Higgins CB, Wexler L. Reversal of dominance of the coronary arterial system in isolated aortic stenosis and bicuspid aortic valve. Circulation 1975;52:292.

166. Hill RC, Chitwood WR Jr, Bashore TM, et al. Coronary flow and regional function before and after supra-arterial myotomy for myocardial bridging. Ann Thorac Surg 1981;31:176.

167. Hillestad L, Eie H. Single coronary artery. Acta Med Scand 1971; 189:409.

168. Hoffman J. The effect of intramyocardial forces on the distribution of intramyocardial blood flow. J Biomed Eng 1979;1:33.

169. Honey M, Lincoln JCR, Osborne MP, et al. Coarctation of the aorta with right aortic arch. Report of surgical correction in two cases: one with associated anomalous origin of left circumflex coronary artery from the right pulmonary artery. Br Heart J 1975;37:937.

170. Housman LB, Morse J, Litchford B, et al. Left ventricular fistula as a cause of intractable angina pectoris. Successful surgical repair. JAMA 1978;240:372.

171. Hughes M. Anomalous origin of the right coronary artery from the left anterior descending coronary artery. Cathet Cardiovasc Diagn 1997;42:308.

172. Huhta JC, Edwards WD, Danielson GK. Supravalvular mitral ridge containing the dominant left circumflex coronary artery. J Thorac Cardiovasc Surg 1981;81:577.

173. Hung K, Hsieh I, Chern M, et al. Pulmonary pseudosequestration receiving arterial supply from a coronary artery fistula. Angiology 1996;47:925.

174. Hurwitz RA, Caldwell RL, Girod DA, et al. Clinical and hemodynamic course of infants and children with anomalous left coronary artery. Am Heart J 1989;118:1176.

175. Hutchins GM, Bulkley BH, Miner MM, et al. Correlation of age and heart weight with tortuosity and caliber of normal human coronary arteries. Am Heart J 1977;94:196.

176. Hutchins GM, Nazarian IH, Bulkley BH. Association of left dominant coronary arterial system with congenital bicuspid aortic valve. Am J Cardiol 1978;42:57.

177. Ilia R, Gilutz H, Gueron M. Mid left anterior descending coronary artery originating from the right coronary artery. Int J Cardiol 1991; 33:162.

178. Ilia R, Jafari J, Weinstein JM, et al. Absent left circumflex coronary artery. Cathet Cardiovasc Diagn 1994;32:349.

179. Ilia R. Anomalous origin of the right coronary artery high above the noncoronary sinus of Valsalva. Cathet Cardiovasc Diagn 1994;35: 184.

180. Ilia R, Weinstein JM, Battler A. Single coronary artery originating above the left sinus of Valsalva. Int J Cardiol 1995;48:97.

181. Shotar A, Busittil A. Myocardial bars and bridges and sudden death. Forensic Sci Int 1994;68:143.

182. Irving GI. The angiographic prevalence of myocardial bridging in man. Chest 1982;81:198.

183. Virmani R, Farb A, Burke AP. Ischemia from myocardial coronary bridging: fact or fancy? Hum Pathol 1993;24:687.

184. Ishii T, Hosoda Y, Osaka T, et al. The significance of myocardial bridge upon atherosclerosis in the left anterior descending coronary artery. J Pathol 1986;148:279.

185. Ishikawa T, Brandt PWT. Anomalous origin of the left main coronary artery from the right anterior aortic sinus: angiographic definition of anomalous course. Am J Cardiol 1985;55:770.

186. Ishikawa T, Otsuka T, Suzuki T. Anomalous origin of the left main coronary artery from the noncoronary sinus of Valsalva. Pediatr Cardiol 1990;11:173.

187. Ishimori T, Raizner AF, Chahine RA, et al. Myocardial bridges in man: clinical correlations and angiographic accentuation with nitroglycerin. Cathet Cardiovasc Diagn 1977;3:59.

188. Isner JM, Shen EM, Martin ET, et al. Sudden unexpected death as a result of anomalous origin of the right coronary artery from the left sinus of Valsalva. Am J Med 1984;76:55.

189. Iversen S, Hake U, Mayer E, et al. Surgical treatment of myocardial bridging causing coronary artery obstruction. Scand J Thorac Cardiovasc Surg 1992;26:107.

190. Jaffe RB, Clancy DL, Epstein SE, et al. Coronary arterial-right heart fistulae. Long-term observations in seven patients. Circulation 1973; 47:133.

191. Jain SP, White CJ, Ventura HO. De novo appearance of a myocardial bridge in heart transplant: assessment by intravascular ultrasonography, Doppler, and angioscopy. Am Heart J 1993;126:453.

192. James TN. Anatomy of the coronary arteries. New York: Paul B. Hoeber, 1961:1–60.

193. Jin Z, Berger F, Uhlemann F, et al. Improvement in left ventricular dysfunction after aortic reimplantation in 11 consecutive pediatric patients with anomalous origin of the left coronary artery from the

pulmonary artery: early results of a serial echocardiographic follow-up. Eur Heart J 1994;15:1044.

194. Johnson AD, Detwiler JH, Higgins CB. Left coronary artery anatomy in patients with bicuspid aortic valves. Br Heart J 1978;40:489.

195. Josa M, Danielson GK, Weidman WH, et al. Congenital ostial membrane of left main coronary artery. J Thorac Cardiovasc Surg 1981; 81:338.

196. Juilliere Y, Berder V, Suty-Selton C, et al. Isolated myocardial bridges with angiographic milking of the left anterior descending coronary artery: a long-term follow-up study. Am Heart J 1995;129:663.

197. Kardos A, Babai L, Rudas L, et al. Epidemiology of congenital coronary artery anomalies: a coronary arteriography study on a Central European population. Cathet Cardiovasc Diagn 1992;42:270.

198. Kelley MJ, Wolfson S, Marshall R. Single coronary artery from the right sinus of Valsalva: angiography, anatomy, and clinical significance. Am J Roentgenol 1977;128:257.

199. Kelm M, Schrader J. Control of coronary vascular tone by nitric oxide. Circ Res 1990;66:1561.

200. Keren A, Tzivoni D, Stern S. Functional consequences of right coronary artery originating from left sinus of Valsalva (letter to editor). Am J Cardiol 1983;51:1241.

201. Kimbiris D, Iskandrian A, Segal BL, et al. Anomalous aortic origin of coronary arteries. Circulation 1978;58:606.

202. King BD, Ambrose JA, Stein JH, et al. Anomalous origin of the right coronary artery from the ascending aorta above the left coronary sinus. Cath Cardiovasc Diag 1982;8:277.

203. Kitazume H, Kramer Jr, Krauthamer D, et al. Myocardial bridges in obstructive hypertrophic cardiomyopathy. Am Heart J 1983;106:131.

204. Klues HG, Schwarz ER, vom Dahl J, et al. Intracoronary stent implantation—a new therapeutical approach in highly symptomatic patients with myocardial bridging. J Am Coll Cardiol 1997;29:220A.

205. Koiwa Y, Bahn RC, Ritman EL. Regional myocardial volume perfused by the coronary artery branch: estimation in vivo. Circulation 1986;74:157.

206. Koops B, Kerber RE, Wexler L, et al. Congenital coronary artery anomalies, experience at Stanford University hospital (1963–1971). JAMA 1973;226:1425.

207. Kracoff OH, Ovsyshcher I, Gueron M. Malignant course of a benign anomaly: myocardial bridging. Chest 1987;92:1113.

208. Kragel AH, Roberts WC. Anomalous origin of either the right or left main coronary artery from the aorta with subsequent coursing between aorta and pulmonary trunk: analysis of 32 necropsy cases. Am J Cardiol 1988;62:771.

209. Krajcer Z, Leachman RD, Lufschanowski R, et al. Anomalous left coronary artery from pulmonary artery. Unusual case complicated by coronary arterial disease and fistula from coronary artery to left ventricle. Chest 1978;74:102.

210. Kramer JR, Kitazume H, Proudfit WI, et al. Clinical significance of isolated coronary bridges: benign and frequent condition involving the left anterior descending artery. Am Heart J 1982;103:283.

211. Kuhn FE, Reagan K, Mohler ER, et al. Evidence for endothelial dysfunction and enhanced vasoconstriction in myocardial bridges. Am Heart J 1991;122:1764.

212. Kurosawa H, Wagenaar SS, Becker AE. Sudden death in a youth. A case of quadricuspid aortic valve with isolation of origin of left coronary artery. Br Heart J 1981;46:211.

213. Kwan T, Feit A, Garcia A, et al. Cardiac catheterization and selective coronary angiography with tortuous aorta and anomalous coronary artery. Angiology 1996;47:705.

214. Ladowski JS, Belvedere DA, Wuest LF. Anomalous origin of the right coronary artery from the pulmonary artery: an unusual cause of angina. Cardiovasc Surg 1995;3:81.

215. Laifer LI, Weiner BH. Percutaneous transluminal coronary angioplasty of a coronary stenosis at the site of myocardial bridging. Cardiology 1991;79:245.

216. Lambert V, Touchot A, Losay J, et al. Midterm results after surgical repair of the anomalous origin of the coronary artery. Circulation 1996;94(Suppl II):38.

217. Latson LA, Forbes TJ, Cheatham JP. Transcatheter coil embolization of a fistula from the posterior descending coronary artery to the right ventricle in a two-year-old child. Am Heart J 1992;124:1624.

218. Lau G. Sudden death arising from a congenital coronary artery fistula. Forens Sci Int 1995;73:125.

219. Lawson A, Dailey M, Soto B. Selective injection of a left coronary

220. Lazar JM, Uretsky BF. Coronary artery fistula after heart transplantation: a disappearing entity? Cathet Cardiovasc Diagn 1996;37:10.

221. Lazarous DF, Scheinowitz M, Shou M, et al. Effects of chronic systemic administration of basic fibroblast growth factor on collateral development in the canine heart. Circulation 1995;91:145.

222. Le TQ, Laskey WK, McLaughin J, et al. Utility of magnetic resonance imaging in a patient with anomalous origin of the right coronary artery, acute myocardial infarction and near-sudden cardiac death. Cathet Cardiovasc Diagn 1997;42:205.

223. Lee SS, Wu TL. The role of mural coronary artery in prevention of coronary atherosclerosis. Arch Path 1972;93:32.

224. Leitch A, Caves PK. A case of Marfan's syndrome with absent right coronary artery complicated by aortic dissection and right ventricular infarction. Thorax 1975;30:352.

225. Lenox CC, Briner J. Absent proximal coronary arteries associated with pulmonary atresia. Am J Cardiol 1972;30:666.

226. Lerberg DB, Ogden JA, Zuberbuhler JR, et al. Anomalous origin of the right coronary artery from the pulmonary artery. Ann Thorac Surg 1979;27:87.

227. Lerer PF, Edwards WD. Coronary arterial anatomy in bicuspid aortic valve: necropsy study of 100 hearts. Br Heart J 1981;45:142.

228. Lesauskaite VV. A sudden death case with myocardial bridge in the left anterior descending artery. Arkh Patol 1988;50:67.

229. Letac B, Cazor JL, Cribier A, et al. Large multiple coronary artery aneurysm in adult patients: a report on three patients and a review of the literature. Am Heart J 1980;99:694.

230. Leung WHL, Stadius ML, Alderman EL. Determinants of normal coronary artery dimensions in humans. Circulation 1991;84:2294.

231. Levin DC, Fellow KE, Abrams HL. Hemodynamically significant primary anomalies of the coronary arteries: angiographic aspects. Circulation 1978;58:25.

232. Levitsky S, van der Horst RL, Hastreiter AR, et al. Anomalous left coronary artery in the infant: recovery of ventricular function following early direct aortic implantation. J Thorac Cardiovasc Surg 1980; 79:598.

233. Lewis BS, Gotsman MS. Relation between coronary artery size and left ventricular wall mass. Br Heart J 1973;35:1150.

234. Liberthson RR, Dinsmore R, Bharati S, et al. Aberrant coronary artery origin from the aorta: diagnosis and clinical significance. Circulation 1974;50:774.

235. Liberthson RR, Dinsmore RE, Fallon JT. Aberrant coronary artery origin from the aorta. Report of 18 patients, review of literature and delineation of natural history and management. Circulation 1979;59: 748.

236. Liberthson RR, Gang DL, Custer J. Sudden death in an infant with aberrant origin of the right coronary artery from the left sinus of Valsalva of the aorta: case report and review of the literature. Pediatr Cardiol 1983;4:45.

237. Liberthson RR, Sagar K, Berkoben JP, et al. Congenital coronary arteriovenous fistula. Report of 13 patients, review of the literature, and delineation of management. Circulation 1979;59:849.

238. Liberthson RR. Sudden death from cardiac causes in children and young adults. N Engl J Med 1996;334:1039.

239. Lim CH, Tan NC, Tan L, et al. Giant congenital aneurysm of the right coronary artery. Am J Cardiol 1977;39:751.

240. Lipsett J, Bryard RW, Carpenter BF, et al. Anomalous coronary arteries arising from the aorta associated with sudden death in infancy and early childhood. Arch Pathol Lab Med 1991;115:770.

241. Lipsett J, Cohle SD, Berry PJ, et al. Anomalous coronary arteries: a multicenter pediatric autopsy study. Pediatr Pathol 1994;14:287.

242. Lipton MJ, Barry WH, Obrez I, et al. Isolated single coronary artery: diagnosis, angiographic classification, and clinical significance. Radiology 1979;130:39.

243. Livingston DR, Mehta AC, O'Donovan PB, et al. Angiographic dilemma: bronchopulmonary sequestration versus pseudosequestration: case report. Angiology 1986;37:896.

244. Longenecker CG, Reemtsma K, Creech O Jr. Surgical implications of single coronary artery: a review and two case reports. Am Heart J 1961;61:382.

245. Lynch P. Soldiers, sport and sudden death. Lancet 1980;1:1235.

246. MacAlpin RN. Clinical significance of myocardial bridges. Am Heart J 1982;104:648.

247. MacAlpin RN, Abbasi AS, Grollman JH, et al. Human coronary artery size during life. Diagn Radiol 1973;108:567.

248. Mahon NG, Sugrue DD. Treatment of a long segment of symptomatic myocardial bridging with multiple coronary stents. J Invas Cardiol 1997;9:484.

249. Mahoney LT, Schieken RM, Lauer RM. Spontaneous closure of a coronary artery fistula in childhood. Pediatr Cardiol 1982;2:311.

250. Mahowald JM, Blieden LC, Coe JI, et al. Ectopic origin of a coronary artery from the aorta. Sudden death in 3 of 23 patients. Chest 1986; 89:668.

251. Maluf MA, Smith M, Abellan DM, et al. Anomalous origin of the right coronary artery from the pulmonary artery in association with a ventricular septal defect. Tex Heart Inst J 1997;24:226.

252. Marik D, Gately HL, Strauss R, Starr A. Anomalous origin of right coronary artery from pulmonary artery. J Cardiac Surg 1995;10:55.

253. Markis JE, Joffe CD, Cohn PF, et al. Clinical significance of coronary arterial ectasia. Am J Cardiol 1976;37:217.

254. Maron BJ, Roberts WC, McAllister HA, et al. Sudden death in young athletes. Circulation 1980;62:218.

255. Mattern AL, Baker WP, McHale JJ, et al. Congenital coronary aneurysms with angina pectoris and myocardial infarction treated with saphenous vein bypass graft. Am J Cardiol 1972;30:906.

256. Mays AE Jr, McHale PA, Greenfield JR Jr. Transmural myocardial blood flow in a canine model of coronary artery bridging. Circ Res 1981;49:726.

257. Marzu A, Ditano G, Cogade K, et al. Myocardial bridging involving more than one site of the left anterior descending coronary artery: an uncommon cause of acute ischemic syndrome. Cathet Cardiovasc Diagn 1995;34:329.

258. McLellan BA, Pelikan PCD. Myocardial infarction due to multiple coronary-ventricular fistulas. Cathet Cardiovasc Diagn 1989;16:247.

259. Menke DM, Jordan MD, Aust CH, et al. Isolated and severe left main coronary atherosclerosis and thrombosis: a complication of acute angle takeoff of the left main coronary artery. Am Heart J 1986;112: 1319.

260. Menke DM, Waller BF, Pless JE. Hypoplastic coronary arteries and high takeoff position of the right coronary ostium. A fatal combination of congenital coronary artery anomalies in an amateur athlete. Chest 1985;88:299.

261. Meyer MH, Stephenson HE, Ketas TE, et al. Coronary artery resection for giant aneurysmal enlargement and arteriovenous fistulae. Am Heart J 1967;74:603.

262. Meyers DG, McManus BM, McCall D, et al. Single coronary artery with the right coronary artery arising from the first septal perforator. Cathet Cardiovasc Diagn 1984;10:479.

263. Mintz GS, Abdulmassih S, Bemis LE, et al. Myocardial ischemia in anomalous origin of the right coronary artery from the pulmonary trunk. Am J Cardiol 1983;51:610.

264. Morales AR, Romanelli R, Boucke RJ. The mural left anterior descending coronary artery, strenuous exercise and sudden death. Circulation 1980;62:230.

265. Morales AR, Romanelli R, Tate LG, et al. Intramural left anterior descending coronary artery: significance of the depth of the muscular tunnels. Hum Pathol 1993;24:693.

266. Morin D, Fischer AP, Sohl BE, et al. Iatrogenic myocardial infarction. A possible complication of mitral valve surgery related to anatomical variation of the circumflex coronary artery. Thorac Cardiovasc Surg 1982;30:176.

267. Moskowitz WB, Newkumet KM, Albrecht GT, et al. Case of steel versus steal: coil embolization of congenital coronary arteriovenous fistula. Am Heart J 1991;121:909.

268. Mouratidis B, Lomas FE, McGill D. Thallium-201 myocardial SPECT in myocardial bridging. J Nucl Med 1995;36:1031.

269. Mukai H, Minemawari Y, Hanawa N, et al. Coronary stenosis and steal phenomenon in coronary-pulmonary fistula—assessment with stress thallium tomography after coronary angioplasty and fistulectomy. Jpn Circ J 1993;57:1021.

270. Munkata K, Sata N, Sasake Y. Two cases of variant from angina pectoris associated with myocardial bridge: a possible relationship among coronary vasospasm, atherosclerosis and myocardial bridge. Jpn Circ J 1992;56:1248.

271. Murphy DA, Roy DL, Sohal M, et al. Anomalous origin of left main coronary artery from anterior sinus of Valsalva with myocardial infarction. J Thorac Cardiovasc Surg 1978;75:282.

272. Muus CJ, McManus BM. Common origin of right and left coronary arteries from the region of left sinus of Valsalva: association with unexpected intrauterine death. Am Heart J 1984;107:1285.

273. Muyldermans LL, Van den Heuvel PA, Ernst SM. Epicardial crossing of coronary arteries: a variation of coronary arterial anatomy. Int J Cardiol 1985;7:416.

274. Nakajima K, Taki J, Bunko H, et al. Demonstration of therapeutic effect in a patient with myocardial bridge by exercise-myocardial SPECT imaging. Clin Nucl Med 1985;10:116.

275. Neches WH, Mathews RA, Park SC, et al. Anomalous origin of the left coronary artery from the pulmonary artery. Circulation 1974;50: 582.

276. Nehgme RA, Dewar ML, Lutin WA, et al. Anomalous left coronary artery from the main pulmonary trunk: physiologic and clinical importance of its association with persistent ductus arteriosus. Pediatr Cardiol 1992;13:97.

277. Neufeld HN, Schneeweiss A. Anomalous origin of the coronary arteries from the pulmonary artery. In: Neufeld NH, Schneeweiss A, eds. Coronary artery disease in infants and children. Vol 1. Philadelphia: Lea & Febiger, 1983:30–40.

278. Nohara R, Kambara H, Murakami T, et al. Giant coronary-to-bronchial artery anastomosis complicated by myocardial infarction. Chest 1983; 84:772.

279. O'Connor WN, Stahr BJ, Cottrill CM, et al. Ventriculocoronary connections in hypoplastic right heart syndrome: autopsy serial section study of six cases. J Am Coll Cardiol 1988;11:1061.

280. O'Keefe JH, Owen RM, Bove AA. Influence of left ventricular mass on coronary artery cross-sectional area. Am J Cardiol 1987;59:1395.

281. Ochsner JL, Mills NL. Surgical management of diseased intracavitary coronary arteries. Ann Thorac Surg 1984;38:356.

282. Ogden JA, Goodyear AVN. Patterns of distribution of the single coronary artery. Yale J Biol Med 1970;43:11.

283. Ogden JA, Stansel HC. The anatomic variability of coronary artery fistulae termination in the right and left atria. Chest 1974;65:76.

284. Ogden JA. Congenital anomalies of the coronary arteries. Am J Cardiol 1970;25:474.

285. Ogden JA. Congenital variations of the coronary arteries. A clinicopathologic survey. A thesis presented to the Faculty of the School of Medicine, Yale University, 1968.

286. Ogden JA. Anomalous aortic origin: circumflex, anterior descending or main left coronary arteries. Arch Pathol 1969;88:323.

287. Okita Y, Miki S, Kusuhara K, et al. Aneurysm of coronary arteriovenous fistula presenting as a calcified mediastinal mass. Ann Thoracic Surg 1992;54:771.

288. Okuyama M, Kubota I, Miura T, et al. Anomalous origin of the right coronary artery from the left ventricle in an adult. Jpn Heart J 1995; 36:115.

289. Onouchi Z, Shimazu S, Kiyosawa N, et al. Aneurysms of the coronary arteries in Kawasaki disease. Circulation 1982;66:6.

290. Oshiro H, Shimabukuro M, Nakada Y, et al. Multiple coronary LV fistulas: demonstration of coronary steal phenomenon by stress thallium scintigraphy and exercise hemodynamics. Am Heart J 1990;120: 217.

291. Ott DA, Cooley DA, Pinsky WW, et al. Anomalous origin of circumflex coronary artery from right pulmonary artery: report of a rare anomaly. J Thorac Cardiovasc Surg 1978;76:190.

292. Page HL, Engel HJ, Campbell WB, et al. Anomalous origin of the left circumflex coronary artery: recognition, angiographic demonstration and clinical significance. Circulation 1974;50:768.

293. Polacek P. Relation of myocardial bridges and loops on the coronary arteries to coronary occlusions. Am Heart J 1961;61:44.

294. Palomo AR, Schrager BR, Chahine RA. Anomalous origin of the right coronary artery from the ascending aorta high above the left posterior sinus of Valsalva of a bicuspid aortic valve. Am Heart J 1985;109: 902.

295. Palomo AR, Schrager BR, Chahine RA. Anomalous separate origin of the septal perforator coronary artery from the left sinus of Valsalva. Cathet Cardiovasc Diagn 1984;10:385.

296. Parashara DK, Ledley GS, Kotler MN, et al. The combined presence of myocardial bridging and fixed coronary artery stenosis. Am Heart J 1993;125:1170.

297. Parsonnet V. Intracavitary coronary arteries. Ann Thorac Surg 1985; 40:206.

298. Patterson FK. Sudden death in a young adult with anomalous origin of the posterior circumflex artery. South Med J 1982;75:748.

299. Paulin SJ. Ectopic origin of the right coronary artery: anterior or posterior—that is the question. Cathet Cardiovasc Diagn 1995;36: 379.

300. Paulsen S, Vetner M, Hagerup CM. Relationship between heart weight and the cross-sectional area of the coronary ostia. Acta Pathol Microbiol Scand 1975;83:529.

301. Perloff JK. Congenital anomalies of the coronary circulation. In: The clinical recognition of congenital heart disease. 4th ed. Philadelphia: WB Saunders, 1994:738.

302. Perry SB, Rome J, Keane JF, et al. Transcatheter closure of coronary artery fistulas. J Am Coll Cardiol 1992;124:1624.

303. Phillips DA, Berman J. A variation in the origin of the posterior descending coronary artery. Cardiovasc Intervent Radiol 1984;7:75.

304. Pichard AD, Casanegra P, Marchant E, et al. Abnormal regional myocardial flow in myocardial bridging of the left anterior descending coronary artery. Am J Cardiol 1981;47:978.

305. Piechaud JF, Shalaby L, Kachaner J, et al. Pulmonary artery "stop-flow" angiography to visualize the anomalous origin of the left coronary artery from the pulmonary artery in infants. Pediatr Cardiol 1987; 8:11.

306. Polacek P, Zechmeister A. The occurrence and significance of myocardial bridges and loops on coronary arteries. Opuscola Cardiologica. Acta Facultatis Medicae Universitatis Brunensis, Brno, Czech Republic, 1968.

307. Portsmann W, Iwig J. Die intramurale Koronaroarterie im Angiogramm. Fortschr Roentenstr 1960;92:129.

308. Rivitz SM, Yasuda T. Predictive value of dipyridamole thallium imaging in a patient with myocardial bridging but without fixed obstructive coronary artery disease. J Nucl Med 1992;33:1905.

309. Probst P, Pachinger O, Koller H, et al. Origin of anterior descending branch of left coronary artery from pulmonary trunk. Br Heart J 1976; 38:523.

310. Raffer SF, Oetgen WJ, Weeks KD Jr, et al. Thallium-201 scintigraphy after surgical repair of hemodynamically significant primary coronary artery anomalies. Chest 1982;81:687.

311. Raht S, Har-Zahav Y, Battler A, et al. Frequency and clinical significance of anomalous origin of septal perforator coronary artery. Am J Cardiol 1986;58:657.

312. Ranniger K, Thilenius OG, Cassels DE. Angiographic diagnosis of an anomalous right coronary artery arising from the pulmonary artery. Radiology 1967;88:29.

313. Reddy K, Mohinder G, Hamby RI. Multiple coronary arteriosystemic fistulas. Am J Cardiol 1974;33:304.

314. Reidy JF, Anjos RT, Qureshi SA, et al. Transcatheter embolization in the treatment of coronary artery fistula. J Am Coll Cardiol 1991; 18:187.

315. Reidy JF, Tynan MJ, Qureshi S. Embolization of a complex coronary arteriovenous fistula in a 6 year old child: the need for specialized embolization techniques. Br Heart J 1990;63:246.

316. Reig J, Ruiz de Miguel C, Moragas A. Morphometric analysis of myocardial bridges in children with ventricular hypertrophy. Pediatr Cardiol 1990;11:186.

317. Rein AJJT, Colan SD, Parness IA, et al. Regional and global left ventricular function in infants with anomalous origin of the left coronary artery from the pulmonary trunk: preoperative and postoperative assessment. Circulation 1987;75:115.

318. Reis RL, Cohen LS, Mason DT. Direct measurement of instantaneous coronary blood flow after total correction of anomalous left coronary artery. Circulation 1969;39:229.

319. Rinaldi RG, Carballido J, Giles R, et al. Right coronary artery with anomalous origin and slit ostium. Ann Thorac Surg 1994;58:829.

320. Rittenhouse EA, Doty DB, Ehrenhaft JL. Congenital coronary artery-cardiac chamber fistula. Ann Thorac Surg 1975;20:468.

321. Rivitz SM, Yasuda T. Predictive value of dipyridamole thallium imaging in a patient with myocardial bridging but without fixed obstructive coronary artery disease. J Nucl Med 1992;33:1905.

322. Roberts WC, Glick BN. Congenital hypoplasia of both right and left circumflex coronary arteries. Am J Cardiol 1992;70:121.

323. Roberts WC, Shirani J. The four subtypes of anomalous origin of the left main coronary artery from the right aortic sinus (or from the right coronary artery). Am J Cardiol 1992;70:119.

324. Roberts WC, Siegel RJ, Zipes DP. Origin of the right coronary artery from the left sinus of Valsalva and its functional consequences: analysis of 10 necropsy patients. Am J Cardiol 1982;49:863.

325. Roberts WC, Silver MA, Sapala JC. Intussusception of a coronary artery associated with sudden death in a college football player. Am J Cardiol 1986;57:179.

326. Roberts WC, Waller BF, Roberts CS. Fatal atherosclerotic narrowing of the right main coronary artery: origin of the left anterior descending or left circumflex coronary artery from the right (the true "left-main equivalent"). Am Heart J 1982;104:638.

327. Roberts WC. Major anomalies of coronary arterial origin seen in adulthood. Am Heart J 1986;111:941.

328. Roberts WJ, Morrow AG. Compression of anomalous left circumflex coronary arteries by prosthetic valve fixation rings. J Thorac Cardiovasc Surg 1969;57:834.

329. Robicsek F. Origin of the left anterior descending coronary artery from the left mammary artery. Am Heart J 1984;108:1377.

330. Robicsek R, Sanger P, Daugherty HK, et al. Origin of the anterior interventricular (descending) coronary artery and vein from the left mammary vessels. A previously unknown anomaly of the coronary system. J Thorac Cardiovasc Surg 1967;53:602.

331. Rodgers DM, Wolf NM, Barrett MJ, et al. Two-dimensional echocardiographic features of coronary arteriovenous fistulae. Am Heart J 1982;104:872.

332. Rose AG. Multiple coronary arterioventricular fistulae. Circulation 1978;58:178.

333. Roughneen PT, Bhattacharjee M, Morris PT, et al. Spontaneous thrombosis in a coronary artery fistula with aneurysmal dilatation of the sinus of Valsalva. Ann Thorac Surg 1994;57:232.

334. Rowe L, Carmody TJ, Askenazi J. Anomalous origin of the left circumflex coronary artery from the right aortic sinus: a familial clustering. Cathet Cardiovasc Diagn 1993;29:277.

335. Roynard JL, Cattan S, Artigou JY, et al. Anomalous course of the left anterior descending coronary artery between the aorta and pulmonary trunk: a rare cause of myocardial ischemia at rest. Br Heart J 1994; 72:397.

336. Rozenman Y, Schechter D, Gilon D, et al. Anomalous origin of the circumflex coronary artery from the right sinus of Valsalva as a cause of ischemia at old age. Clin Cardiol 1993;16:900.

337. Ruiz CE, Lau FYK. Congenital atresia of left main coronary artery: proposed mechanism for severe disabling angina in a patient with non-atherosclerotic single right coronary artery. A case report. Cathet Cardiovasc Diagn 1991;23:190.

338. Ruszkiewicz A, Opeskin K. Sudden death in pregnancy from congenital malformation of the coronary arteries. Pathology 1993;25:236.

339. Sabiston DC Jr, Neill CA, Taussig HB. Direction of blood flow in anomalous left coronary artery arising from the pulmonary artery. Circulation 1960;22:591.

340. Sacks JH, Londe SP, Rosenbluth A, et al. Left main coronary bypass for aberrant (aortic) intramural left coronary artery. J Thorac Cardiovasc Surg 1977;73:733.

341. Sagkan O, Ornek E, Yesildag O. Left circumflex coronary artery arising as a terminal extension of right coronary artery. A case report. Angiology 1994;45:405.

342. Said SA, Bucx JJ, van de Weel FA. Stress MIBI scintigraphy in multiple coronary-pulmonary fistula: failure to demonstrate "steal" phenomenon. Int J Cardiol 1992;35:270.

343. Said SAM, El Gamal MIH, van der Werf T. Coronary arteriovenous fistulas: collective review and management of six new cases—changing etiology, presentation and treatment strategy. Clin Cardiol 1997; 20:748.

344. Saji T, Yamamoto K, Hashiguchi R, et al. Hypoplastic left coronary artery in association with occlusive thickening of a coronary artery with ectopic ostium and with atresia of the left coronary ostium. Jpn Heart J 1985;26:603.

345. Saner HE, Saner BD, Dykoski RK, et al. Origin of anterior descending coronary artery from the first septal perforator. Cathet Cardiovasc Diagn 1984;10:479.

346. Sasson Z, Grande P, Lorett I, et al. Proximal narrowing of anomalous right coronary artery from the left coronary sinus: delineation by Omniplane transesophageal echocardiogram. Can J Cardiol 1996;12:529.

347. Savic B, Birtel FJ, Tholen W, et al. Lung sequestration: report of seven cases and review of 540 published cases. Thorax 1979;34:96.

348. Schang SJ, Pepine CJ, Bemiller CR. Anomalous coronary origin and bicuspid aortic valve. Vasc Surg 1975;9:67.

349. Schaper W, Schaper J. Collateral circulation. Norwell, MA: Kluwer Academic Publishers, 1993.

350. Schlesinger MJ, Zoll PM, Wessler S. The conus artery: a third coronary artery. Am Heart J 1949;38:823.

351. Schlesinger MJ. An injection plus dissection study of coronary artery occlusions and anastomosis. Am Heart J 1938;15:528.

352. Schulte MA, Waller BF, Hull MT, et al. Origin of the left anterior descending coronary artery from the right aortic sinus with intramyocardial tunneling to the left side of the heart via the ventricular septum: a case against clinical and morphologic significance of myocardial bridging. Am Heart J 1985;110:499.

353. Schwarz ER, Klues HG, Dahl J, et al. Functional, angiographic and intracoronary Doppler flow characteristics in symptomatic patients with myocardial bridging: effect of short-term intravenous betablocker medication. J Am Coll Cardiol 1996;27:1637.

354. Seabra-Gomes R, Somerville J, Ross DN, et al. Congenital coronary artery aneurysms. Br Heart J 1974;36:329.

355. Serota H, Barth CW, Seus CA, et al. Rapid identification of the course of anomalous coronary arteries in adults: the "dot" and "eye" method. Am J Cardiol 1990;65:891.

356. Sharbaugh AH, White RS. Single coronary artery. Analysis of the anatomic variation, clinical importance, and report of five cases. JAMA 1974;230:243.

357. Shigenobu M, Ohta T, Senoo Y, et al. Congenital coronary aneurysm associated with a single coronary artery. Cardiovasc Surg 1993;1:79.

358. Shiode N, Kato M, Teragawa H, et al. Vasomotility and nitric oxide bioactivity of the bridging segments of the left anterior descending coronary artery. Am J Cardiol 1998;81:341.

359. Shirai K, Ogawa M, Kawaguchi H, et al. Acute myocardial infarction due to thrombus formation in congenital coronary artery fistula. Eur Heart J 1994;15:577.

360. Shirani J, Roberts WC. Solitary coronary ostium in the aorta in the absence of other major congenital cardiovascular anomalies. J Am Coll Cardiol 1993;21:137.

361. Shirani J, Roberts WD. Coronary ostial dimple (in the posterior aortic sinus) in the absence of other coronary arterial abnormalities. Am J Cardiol 1993;72:118.

362. Shirani J, Zafari AM, Roberts WC. Sudden death, right ventricular infarction, and abnormal right ventricular intramural coronary arteries in isolated congenital valvular pulmonic stenosis. Am J Cardiol 1993; 72:368.

363. Shivalkar B, Borgers M, Daenen W, et al. ALCAPA syndrome: an example of chronic myocardial hypoperfusion? J Am Coll Cardiol 1994;23:772.

364. Shubrooks SJ Jr, Naggar CZ. Spontaneous near closure of coronary artery fistula. Circulation 1978;57:197.

365. Silverman KJ, Bulkley BH, Hutchins GM. Anomalous left circumflex coronary artery: "normal" variant of uncertain clinical and pathologic significance. Am J Cardiol 1978;41:1311.

366. Silverman ME, White CS, Ziskind AA. Pulmonary sequestration receiving arterial supply from the left circumflex coronary artery. Chest 1994;106:948.

367. Sing SP, Soto B, Nath H. Anomalous origin of posterior descending artery with unusual intraseptal course. J Thorac Imaging 1994;9:255.

368. Skimming JW, Gessner IH, Victorica BE, et al. Percutaneous transcatheter occlusion of coronary artery fistula using detachable balloons. Pediatr Cardiol 1995;16:38.

369. Skimming JW, Walls JT. Congenital coronary artery fistula suggesting a "steal phenomenon" in a neonate. Pediatr Cardiol 1993;14:174.

370. Sones FM, Shirey EK. Cine coronary arteriography. Mod Conc Cardiovasc Dis 1962;31:735.

371. Sorrell VL, Davis MJ, Bove AA. Current knowledge and significance of coronary artery ectasia: a chronologic review of the literature, recommendations for treatment, possible etiologies, and future considerations. Clin Cardiol 1998;21:157.

372. Spindola FH, Grose R, Solomon N. Dual left anterior descending coronary artery: angiographic description of important variants and surgical implications. Am Heart J 1983;105:445.

373. St. John Sutton MG, Miller GA, Kerr IH, et al. Coronary steal via large coronary artery to bronchial artery anastomosis successfully treated by operation. Br Heart J 1980;44:460.

374. Stables RH, Knight CJ, Neill JG, et al. Coronary stenting in the management of myocardial ischaemia caused by muscle bridging. Br Heart J 1995;74:90.

375. Stauffer JC, Sigwart U, Vogt P, et al. Transluminal angioplasty of a single coronary artery. Am Heart J 1991;122:569.

376. Stein PD, Marzilli M, Sabbah HN, et al. Systolic and diastolic pressure gradients within the left ventricular wall. Am J Physiol 1980;238:625.

377. Steinberg I, Holswade GR. Coronary arteriovenous fistula. AJR 1972; 116:82.

378. Sundar AS, Fox KA. Anomalous origin of the right coronary artery from the pulmonary artery in association with congenital aneurysm of the sinus of Valsalva: angiographic diagnosis of a rare association. Br Heart J 1992;68:330.

379. Swanton RH, Thomas ML, Coltart DJ, et al. Coronary artery ectasia—a variant of occlusive coronary arteriosclerosis. Br Heart J 1978; 40:393.

380. Swaye PS, Fisher LD, Litwin P, et al. Aneurysmal coronary artery disease. Circulation 1983;67:134.

381. Taber RE, Gale MH, Lam CR. Coronary artery-right heart fistulas. J Thorac Cardiovasc Surg 1967;53:84.

382. Takahasi M, Sekiguchi H, Fujikawa H, et al. Multicystic aneurysmal dilatation of bilateral coronary artery fistula. Cathet Cardiovasc Diagn 1994;31:290.

383. Taylor AJ, Byers JP, Cheitlin MD, et al. Anomalous right or left coronary artery from the contralateral coronary sinus: "high-risk" abnormalities in the initial coronary artery course and heterogeneous clinical outcomes. Am Heart J 1997;133:428.

384. Taylor AJ, Farb A, Ferguson M, et al. Myocardial infarction associated with physical exertion in a young man. Circulation 1997;96:3201.

385. Taylor AJ, Rogan KM, Virmani R. Sudden cardiac death associated with isolated congenital coronary artery anomalies. J Am Coll Cardiol 1992;20:640.

386. Teno LA, Santos JL, Bestetti RB, et al. Congenital circumflex coronary artery fistula with drainage into the left ventricle. Tex Heart Inst J 1993;20:304.

387. Tingelstad JB, Lower RR, Eldredge WJ. Anomalous origin of the right coronary artery from the main pulmonary artery. Am J Cardiol 1972;30:670.

388. Tio RA, Van Gelder IC, Boonstra PW, et al. Myocardial bridging in a survivor of sudden cardiac near-death: role of intracoronary Doppler flow measurements and angiography during dobutamine stress in the clinical evaluation. Heart 1997;77:280.

389. Tkebuchava T, Von Segesser LK, Vogt PR, et al. Congenital coronary fistulas in children and adults: diagnosis, surgical technique and results. J Cardiovasc Surg 1996;37:29.

390. Topaz O, DeMarchena EJ, Perin E, et al. Anomalous coronary arteries: angiographic findings in 80 patients. Int J Cardiol 1992;34:129.

391. Topaz O, DiSciascio G, Vetrovec GW, et al. Absent left main coronary artery: angiographic findings in 83 patients with separate ostia of the left anterior descending and circumflex arteries at the left aortic sinus. Am Heart J 1991;122:447.

392. Topaz O, DiSciascio G, Goudreau E, et al. Coronary angioplasty of anomalous right coronary arteries: notes on technical aspects. Cathet Cardiovasc Diagn 1990;21:106.

393. Topaz O, Edwards JE. Pathologic features of sudden death in children, adolescents, and young adults. Chest 1985;87:476.

394. Trivellato M, Angelini P, Leachman RD. Variations in coronary artery anatomy: normal versus abnormal. Cardiovasc Dis Bull Tex Heart Inst 1980;7:357.

395. Tuna IC, Bessinger FB, Ophoven JP, et al. Acute angular origin of left coronary artery from aorta: an unusual cause of left ventricular failure in infancy. Pediatr Cardiol 1989;10:39.

396. Ueda K, Saito A, Nakano H, et al. Absence of proximal coronary arteries with pulmonary atresia. Am Heart J 1983;106:596.

397. Upshaw CB. Congenital coronary arteriovenous fistula. Report of a case with an analysis of seventy-three reported cases. Am Heart J 1962;63:399.

398. Urcelay GE, Iannettoni MD, Ludomirsky A, et al. Origin of both coronary arteries from the pulmonary artery. Circulation 1994;90: 2379.

399. Urrutia-S CO, Falaschi G, Ott DA, et al. Surgical management of 56 patients with congenital coronary artery fistulae. Ann Thorac Surg 1983;35:300.

400. Vairo U, Marino B, De Simone G, et al. Early congestive heart failure due to origin of the right coronary artery from the pulmonary artery. Chest 1992;102:1610.

401. Van Brussel BL, Van Tellingen C, Ernst SMPG, et al. Myocardial bridging: a cause of myocardial infarction? Int J Cardiol 1984;6:78.

402. van den Brand M, Pieterman H, Suryapranata H, et al. Closure of a

coronary fistula with a transcatheter implantable coil. Cathet Cardiovasc Diagn 1992;25:223.

403. van den Brandhof G, Zijlstra F. Separate origin of a large septal perforator branch. Cathet Cardiovasc Diagn 1992;25:151.

404. Van der Hauwaert L, Dumoulin M, Moerman P. Congenital atresia of the left coronary ostium. Br Heart J 1982;48:298.

405. Vasan RS, Bahl VK, Rajani M. Myocardial infarction associated with a myocardial bridge. Int J Cardiol 1989;25:240.

406. Vavuranakis M, Bush CA, Boudoulas H. Coronary artery fistulas in adults: incidence, angiographic characteristics, natural history. Cathet Cardiovasc Diagn 1995;35:116.

407. Velican D, Petrescu C, Velican C. The branching anatomical pattern of the coronary arteries as a risk factor for coronary heart disease. Med Interne 1981;19:173.

408. Vieweg WVR, Alpert JS, Hagan AD. Caliber and distribution of normal coronary arterial anatomy. Cathet Cardiovasc Diagn 1976;2:269.

409. Virmani R, Chun PKC, Golstein RE, et al. Acute takeoffs of the coronary arteries along the aortic wall and congenital coronary ostial valve-like ridges: association with sudden death. J Am Coll Cardiol 1984;3:766.

410. Virmani R, Patrick K, Kevin R. Anomalous origin of four coronary ostia from the right sinus of Valsalva. Am J Cardiol 1989;63:760.

411. Virmani R, Rogan K, Cheitlin MD. Congenital coronary artery anomalies: pathologic aspects. In: Virmani R, Forman MB, eds. Nonatherosclerotic ischemic heart disease. New York: Raven Press, 1989:153.

412. Vliegen HW, Doornbos J, de Roos A, et al. Value of fast gradient echo magnetic resonance angiography as an adjunct to coronary arteriography in detecting and confirming the course of clinically significant coronary artery anomalies. Am J Cardiol 1997;79:773.

413. Vlodaver Z, Neufeld HN, Edwards JE. Pathology of coronary disease. Semin Roentgenol 1972;7:376.

414. Vlodaver Z, Neufield HN, Edwards JE. Coronary arterial variations in the normal heart and in congenital heart disease. New York: Academic Press 1975:171.

415. Vogelbach KH, Edmiston A, Stenson RE. Coronary artery-left ventricle communications: a report of two cases and review of the literature. Cathet Cardiovasc Diagn 1979;5:159.

416. Vogt PR, Tkebuchava T, Arbenz U, et al. Anomalous origin of the right coronary artery from the pulmonary artery. Thorac Cardiovasc Surgeon 1994;42:125.

417. Voss H, Kupper W, Hanrath P, et al. Clinical correlations, lactate extraction, coronary venous blood flow and thallium-201 myocardial imaging in patients with isolated left anterior descending muscle bridges: normal variant or obstruction? Z Kardiol 1980;69:347.

418. Voudris V, Salachas A, Saounotsou M, et al. Double left anterior descending artery originating from the left and right coronary artery: a rare coronary artery anomaly. Cathet Cardiovasc Diagn 1993;30: 45.

419. Vuthoori S, Waisser E, Angelini P. Triple origin of left coronary arteries from right coronary artery: unusual case of single coronary artery. Clin Cardiol 1980;3:67.

420. Wald S, Stonecipher K, Baldwin BJ, et al. Anomalous origin of the right coronary artery from the pulmonary artery. Am J Cardiol 1971; 27:677.

421. Waller BF. Five coronary ostia: duplicate left anterior descending and right conus coronary arteries. Am J Cardiol 1983;51:1562.

422. Wang A, Pulsipher MW, Jaggers J, et al. Simultaneous biplane coronary and pulmonary arteriography: a novel technique for defining the course of an anomalous left main coronary artery originating from the right sinus of Valsalva. Cathet Cardiovasc Diagn 1997;42:73.

423. Warren SE, Alpert JS, Vieweg WVR, et al. Normal single coronary artery and myocardial infarction. Chest 1977;72:540.

424. Weinberger I, Rotenberg Z, Fuchs J, et al. Myocardial infarction in young adults under 30 years: risk factors and clinical course. Clin Cardiol 1987;10:9.

425. Wenger NK, Peace RJ. Rudimentary left coronary artery. Am J Cardiol 1961;8:519.

426. Wesselhoeft H, Fawcett JS, Johnson AL. Anomalous origin of the left coronary artery from the pulmonary trunk: its clinical spectrum, pathology, and pathophysiology, based on a review of 140 cases with seven further cases. Circulation 1968;38:403.

427. Wilde P, Watt I. Congenital coronary artery fistulae: six new cases with a collective review. Clin Radiol 1980;31:301.

428. Wilens SL, Plair CM, Henderson DH. Size of the major epicardial coronary arteries at necropsy: relation to age, heart, weight, and myocardial infarction. JAMA 1966;198:1325.

429. Wilkins CE, Betancourt B, Mathur VS. Coronary artery anomalies: a review of more than 10,000 patients from the Clayton Cardiovascular Laboratories. Tex Heart Inst J 1988;15:166.

430. Wilson CS, Weaver WF, Zeman ED, et al. Bilateral nonfistulous congenital coronary arterial aneurysms. Am J Cardiol 1975;35:319.

431. Wilson GJ, Freedom RM, Koike K, et al. The coronary arteries: anatomy and histopathology. In: Freedom RM, ed. Pulmonary atresia with intact ventricular septum. New York: Futura Publishing, 1989:75.

432. Woldow AB, Goldstein S, Yazdanfar S. Angiographic evidence of right coronary bridging. Cathet Cardiovasc Diagn 1994;32:351.

433. Yamagishi M, Haze K, Tamai J, et al. Visualization of isolated conus artery as a major collateral pathway in patients with total left anterior descending artery occlusion. Cathet Cardiovasc Diagn 1988;15:95.

434. Yamabe H, Fujitani K, Mizutani T, et al. Two cases of myocardial infarction with coronary arteriovenous fistula. Jpn Heart J 1983;24: 303.

435. Yamanaka O, Hobbs RE. Coronary artery anomalies in 126,595 patients undergoing coronary angiography. Cathet Cardiovasc Diagn 1990;21:28.

436. Yeoh JK, Ling LH, Maurice C. Percutaneous transluminal angioplasty of anomalous right coronary artery arising from the ascending thoracic aorta. Cathet Cardiovasc Diagn 1994;32:254.

437. Zimmerman FH, Cameron A, Fisher LD, et al. Myocardial infarction in young adults: angiographic characterization, risk factors and prognosis (Coronary Artery Surgery Study Registry). J Am Coll Cardiol 1995;26:654.

438. Zumbo O, Fani K, Jarmolych J, et al. Coronary atherosclerosis and myocardial infarction in hearts with anomalous coronary arteries. Lab Invest 1965;14:571.

439. Kolodziej AW, Lobo FV, Walley VM. Intra-atrial course of the right coronary artery and its branches. Can J Cardiol 1994;10:263.

440. Lerer PK, Edwards WD. Coronary arterial anatomy in bicuspid aortic valve. Necropsy study of 100 hearts. Br Heart J 1981;45:142.

441. Krabill KA, Hunter DW. Transcatheter closure of congenital coronary arterial fistula with a detachable balloon. Pediatr Cardiol 1993;14: 176.

442. Ramo OJ, Totterman KJ, Harjula AL. Thrombosed coronary artery fistula as a cause of paroxysmal atrial fibrillation and ventricular arrhythmia. Cardiovasc Surg 1994;2:720.

443. Liu PR, Leong KH, Lee PC, et al. Congenital coronary artery-cardiac chamber fistulae: a study of fourteen cases. (Chung Hua i Hsueh Tsa Chih [Taipei])—Chin Med J 1994;54:160.

444. Davis JT, Allen HD, Wheller JJ, et al. Coronary artery fistula in the pediatric age group: a 19-year institutional experience. Ann Thorac Surg 1994;58:760.

445. Millaire A, Goullard L, De Groote P, et al. Congenital high flow coronary cameral fistula in an 81-year-old woman: management problems. Can J Cardiol 1992;8:917.

446. Ludomirsky A, O'Laughlin MP, Reul GJ, et al. Congenital aneurysm of the right coronary artery with fistulous connection to the right atrium. Amer Heart J 1990;119:672.

447. Rosenberg H, Williams WG, Trusler GA, et al. Congenital aortico-right atrial communications. The dilemma of differentiation from coronary-cameral fistula. J Thorac Cardiovasc Surg 1986;91:841.

448. Ryan C, Gertz EW. Fistula from coronary arteries to left ventricle after myocardial infarction. Br Heart J 1977;39:1147.

449. Lin FC, Chang HJ, Chern MS, et al. Multiplane transesophageal echocardiography in the diagnosis of congenital coronary artery fistula. Am Heart J 1995;130:1236.

450. Alkhulaifi AM, Horner SM, Pugsley WB, et al. Coronary artery fistulas presenting with bacterial endocarditis. Ann Thorac Surg 1995;60: 202.

451. Santoro G, di Carlo D, Carotti A, et al. Origin of both coronary arteries from the pulmonary artery and aortic coarctation. Ann Thorac Surg 1995;60:706.

452. Berdjis F, Takahashi M, Wells WJ, et al. Anomalous left coronary artery from the pulmonary artery. Significance of intercoronary collaterals. J Thorac Cardiovasc Surg 1994;108:17.

453. Perper JA, Rozin L, Williams KE. Sudden unexpected death following exercise and congenital anomalies of coronary arteries. A report of two cases. Am J Forens Med Pathol 1985;6:289.

454. Alexi-Meskishvili V, Hetzer R, Weng Y, et al. Anomalous origin of

the left coronary artery from the pulmonary artery. Early results with direct aortic reimplantation. J Thorac Cardiovasc Surg 1994;108:354.

455. Koh E, Nakagawa M, Hamaoka K, et al. Congenital atresia of the left coronary ostium: diagnosis and surgical treatment. Pediatr Cardiol 1989;10:159.

456. Maron BJ, Leon MB, Swain JA, et al. Prospective identification by two-dimensional echocardiography of anomalous origin of the left main coronary artery from the right sinus of Valsalva. Am J Cardiol 1991;68:140.

457. Spring DA, Thomsen JH. Severe atherosclerosis in the "single coronary artery." Report of a previously undescribed pattern. Am J Cardiol 1973;31:662.

458. Hackenseller H. Ueber akgessorische, von der arteria pulmonalis abgehende Herzgefaesse und ihre Bedeutung fuer das Verstaendnis der formalen Genese des Ursprunges einer oder beider Coronararterien von der Lungenschlagader. Frankf Z Pathol 1955;66:463.

459. Baird RJ, Manktelow RT, Shah PA, et al. Intramyocardial pressure. A study of its regional variations and its relationship to intraventricular pressure. J Thorac Cardiovasc Surg 1970;59:810.

460. Machado C, Bhasin S, Soulen RL. Confirmation of anomalous origin of the right coronary artery from the left sinus of Valsalva with magnetic resonance imaging. Chest 1993;104:1284.

461. Basso C, Frescura C, Corrado D, et al. Congenital heart disease and sudden death in the young. Hum Pathol 1995;26:1065.

462. Post JC, van Rossum AC, Bronzwaer JG, et al. Magnetic resonance angiography of anomalous coronary arteries. A new gold standard for delineating the proximal course? Circulation 1995;92:3163.

463. McConnell MV, Ganz P, Selwyn AP, et al. Identification of anomalous coronary arteries and their anatomic course by magnetic resonance coronary angiography. Circulation 1995;92:3158.

464. Eguchi S, Nitta H, Asano K, et al. Congenital fistula of the right coronary artery to the left ventricle. The third case in the literature. Am Heart J 1970;80:242.

465. Keeton BR, Keenan DJ, Monro JL. Anomalous origin of both coronary arteries from the pulmonary trunk. Br Heart J 1983;49:397.

466. Galbraith AJ, Werner D, Cutforth RH. Fistula between left coronary artery and superior vena cava. Br Heart J 1981;46:99.

467. Hamilton JR, Mulholland HC, O'Kane HO. Origin of the left coronary artery from the right pulmonary artery: a report of successful surgery in a 3-month-old child. Ann Thorac Surg 1986;41:446.

468. Kirklin JW, Barratt-Boyes BG. Congenital anomalies of the coronary arteries. In: Kirklin JW, Barratt-Boyes BG, eds: Cardiac surgery. New York: Churchill Livingstone, 1993:1179-1189.

469. Mustafa I, Gula G, Radley-Smith R, et al. Anomalous origin of the left coronary artery from the anterior aortic sinus: a potential cause of sudden death. Anatomic characterization and surgical treatment. J Thorac Cardiovasc Surg 1981;82:297.

470. Barthe JE, Benito M, Sala J, et al. Double right coronary artery. Am J Cardiol 1994;73:622.

471. Cafferky EA, Crawford DW, Turner AF, et al. Congenital aneurysm of the coronary artery with myocardial infarction. Am J Med Sci 1969;257:320.

472. Casta A. Hypoplasia of the left coronary artery complicated by reversible myocardial ischemia in a newborn. Am Heart J 1987;114:1238.

473. Piovesana P, Corrado D, Verlato R, et al. Morbidity associated with anomalous origin of the left circumflex coronary artery from the right aortic sinus. Am J Cardiol 1989;63:762.

474. Roberts WC. Anomalous origin of both coronary arteries from the pulmonary artery. Am J Cardiol 1962;10:595.

475. Beretta L, Lemma M, Santoli C. Isolated atresia of the left main coronary artery in an adult. Eur J Cardiothorac Surg 1990;4:169.

476. Nelson-Piercy C, Rickards AF, Yacoub MH. Aberrant origin of the right coronary artery as a potential cause of sudden death: successful anatomical correction. Br Heart J 1990;64:208.

477. Baffa JM, Chen SL, Guttenberg ME, et al. Coronary artery abnormalities and right ventricular histology in hypoplastic left heart syndrome. J Am Coll Cardiol 1992;20:350.

478. Bjork L. Ectasia of the coronary arteries. Radiology 1966;87:33.

479. Murphy ML. Single coronary artery. Am Heart J 1967;74:557.

480. Angelini P. Normal and anomalous coronary arteries: definitions and classification. Am Heart J 1989;117:418.

481. Chu E, Cheitlin MD. Diagnostic considerations in patients with suspected coronary artery anomalies. Am Heart J 1993;126:1427.

482. Smith SC, Taber MT, Robiolio PA, et al. Acute myocardial infarction

caused by a myocardial bridge treated with intracoronary stenting. Cathet Cardiovasc Diagn 1997;42:209.

483. Noble J, Bourassa MG, Petitclerc R, et al. Myocardial bridging and milking effect of the left anterior descending coronary artery: normal variant or obstruction? Am J Cardiol 1976;37:993.

484. Raghib G, Bloemendaal RD, Kanjuh VI, et al. Aortic atresia and premature closure of foramen ovale. Myocardial sinusoids and coronary arteriovenous fistula serving as outflow channel. Am Heart J 1965;70:476.

485. Crocker DW, Sobin S, Thomas WC. Aneurysm of the coronary arteries. Am J Pathol 1957;33:819.

486. Cohen LS, Shaw LD. Fatal myocardial infarction in an 11 year old boy associated with a unique coronary artery anomaly. Am J Cardiol 1967;19:420.

487. Harris PN. Aneurysmal dilatation of the cardiac coronary arteries. Am J Pathol 1937;13:89.

488. Nath A, Kennett JD, Politte LL, et al. Anomalous right coronary artery arising from the midportion of the left anterior descending coronary artery—case reports. Angiology 1987;38:142.

489. Barth CW, Bray M, Roberts WC. Sudden death in infancy associated with origin of both left main and right coronary arteries from a common ostium above the left sinus of Valsalva. Am J Cardiol 1986;57:365.

490. Koh KK. Confirmation of anomalous origin of the right coronary artery from the left sinus of Valsalva by means of transesophageal echocardiography. Am Heart J 1991;122:851.

491. Roberts WC, Dicicco BS, Waller BF, et al. Origin of the left main from the right coronary artery or from the right aortic sinus with intramyocardial tunneling to the left side of the heart via the ventricular septum. The case against clinical significance of myocardial bridge or coronary tunnel. Am Heart J 1982;104:303.

492. Fortuin NJ, Roberts WC. Congenital atresia of the left main coronary artery. Am J Med 1971;50:385.

493. Scott DH. Aneurysms of the coronary arteries. Br Heart J 1948;36:403.

494. Thomas D, Salloum J, Montalescot G, et al. Anomalous coronary arteries coursing between the aorta and pulmonary trunk: clinical indications for coronary artery bypass. Eur Heart J 1991;12:832.

495. Fernandes ED, Kadivar H, Hallman GL, et al. Congenital malformations of the coronary arteries: the Texas Heart Institute experience. Ann Thorac Surg 1992;54:732.

496. Sauer U, Gittenberger-de Groot AC, Geishauser M, et al. Coronary arteries in the hypoplastic left heart syndrome. Histopathologic and histometrical studies and implications for surgery. Circulation 1989;80:1168.

496. Partridge JB. High leftward origin of the right coronary artery. Int J Cardiol 1986;13:83.

498. Pollack BD, Belkin RN, Lazar S, et al. Origin of all three coronary arteries from separate ostia in the right sinus of Valsalva: a rarely reported coronary artery anomaly. Cathet Cardiovasc Diagn 1992;26:26.

499. Rakusan K, Flanagan MF, Geva T, et al. Morphometry of human coronary capillaries during normal growth and the effect of age in left ventricular pressure-overload hypertrophy. Circulation 1992;86:38.

500. Line DE, Babb JD, Pierce WS. Congenital aortic valve anomaly. Aortic regurgitation with left coronary artery isolation. J Thorac Cardiovasc Surg 1979;77:533.

501. Kurnik PB, Heymann WR. Coronary artery ectasia associated with hereditary hemorrhagic telangiectasia. Arch Intern Med 1989;149:2357.

502. Liberthson RR. Congenital anomalies of the coronary arteries. Cardiovasc Med 1984;9:857.

503. Goldblatt E, Adams AP, Ross IK, et al. Single-trunk anomalous origin of both coronary arteries from the pulmonary artery. Diagnosis and surgical management. J Thorac Cardiovasc Surg 1984;87:59.

504. Roberts WC, Kragel AH. Anomalous origin of either the right or left main coronary artery from the aorta without coursing of the anomalistically arising artery between aorta and pulmonary trunk. Am J Cardiol 1988;62:1263.

505. James TN. Anatomy of the coronary arteries in health and disease. Circulation 1965;32:1020.

506. Boucek RJ, Morales AR, Romanelli R, et al. Coronary artery disease: pathologic and clinical assessment. Baltimore: Williams & Wilkins, 1984:38.

507. Vollebergh FE, Becker AE. Minor congenital variations of cusp size in tricuspid aortic valves. Possible link with isolated aortic stenosis. Br Heart J 1977;39:1006.
508. Baroldi G, Scomazzoni G. Coronary circulation in the normal heart and the pathologic heart. Washington DC: United States Government Printing Office, 1967.
509. Maseri A. Ischemic heart disease: a rational basis for clinical practise and clinical research. 1st ed. New York: Churchill Livingston, 1995: 71.
510. Harrison DG, Bates JN. The nitrovasodilators. New ideas about old drugs. Circulation 1991;87:1461.
511. Hori M, Kitakaze M. Adenosine, the heart, and coronary circulation. Hypertension 1991;18:565.
512. Liang BT. Adenosine receptors and cardiovascular function. Trends Cardiovasc Med 1992;2:100.
513. Van Camp SP, Bloor CM, Mueller FO, et al. Nontraumatic sports death in high school and college athletes. Med Sci Sports Exerc 1995; 27:641.
514. Maron BJ, Shirani J, Poliac LC, et al. Sudden death in young competitive athletes: clinical, demographic, and pathological profiles. JAMA 1996;276:199.
515. Corrado D, Thiene G, Nava A, et al. Sudden death in young competitive athletes: clinicopathologic correlations in 22 cases. Am J Med 1990;89:588.
516. Virmani R, Robinowitz M, McAllister HA Jr. Nontraumatic death in joggers: a series of 30 patients at autopsy. Am J Med 1982;72:874.
517. Waller BF, Roberts WC. Sudden death while running in conditioned runners aged 40 years or over. Am J Cardiol 1980;45:1292.
518. Thompson PD, Stern MP, Williams P, et al. Death during jogging or running: a study of 18 cases. JAMA 1979;242:1265.
519. Schlant RC, Blomqvist CG, Brandenburg RO, et al. Guidelines for exercise testing: a report of the Joint American College of Cardiology/American Heart Association Task Force on Assessment of Cardiovascular Procedures (Subcommittee on Exercise Testing). Circulation 1986;74:653A.
520. Corrado D, Basso C, Poletti A, et al. Sudden death in the young: is coronary thrombosis the major precipitating factor? Circulation 1994; 90:2315.
521. Mitchell JH, Maron BJ, Epstein SE. 16th Bethesda Conference: cardiovascular abnormalities in the athlete: recommendations regarding eligibility for competition: October 3–5, 1984. J Am Coll Cardiol 1985;6:1186.
522. Suzuki A, Kamiya T, Juwahara N, et al. Coronary arterial lesions of Kawasaki disease: Cardiac catheterization findings of 1100 cases. Pediatr Cardiol 1986;7:3.
523. Kiso I, Itoh T, Morishita M, et al. Blood flow and pressure measurements of right coronary artery to left ventricle fistula. Thorax 1978; 33:253.
524. Grollman JH Jr. The fistulous connection: how does it go? Cathet Cardiovasc Diag 1998;43(2):184.
525. Wearn JT, Mettier SR, Klumpp TG, et al. The nature of the vascular communications between the coronary arteries and the chambers of the heart. Am Heart J 1933;9:143.
526. Acierno LJ. The history of cardiology. London: The Parthenon Publishing Group, 1994:3–39.
527. Lo PH, Chang KC, Hung JS, et al. Anomalous origin of left main coronary artery from the noncoronary sinus: an intravascular ultrasound observation. Cathet Cardiovasc Diagn 1997;42:430.
528. Diez JG, Angelini P, Lee VV. Does the anomalous congenital origin of a coronary artery predispose to the development of stenotic atherosclerotic lesions in its proximal segment? Circulation 1997;96(Suppl I):I-154.
529. Ishikawa T, Otsuka T, Suzuki T. Anomalous origin of the left main coronary artery from the noncoronary sinus of Valsalva. Pediatr Cardiol 1990;11:173.
530. Nomina Anatomica, 6th ed. Edinburgh: Churchill-Livingstone, 1989.
531. O'Malley CD, Saunders JB. Leonardo da Vinci on the human body. New York: Greenwich House, 1982:86–142.
532. Mahowald JM, Blieden LC, Coe JI, et al. Ectopic origin of a coronary artery from the aorta: sudden death in 3 of 23 patients. Chest 1986; 89:668.
533. Hiraishi S, Misawa H, Horiguchi Y, et al. Effect of suture closure of coronary artery fistula on aneurysmal coronary artery and myocardial ischemia. Am J Cardiol 1998;81:1263.
534. Maron BJ, Thompson PD, Puffer JC, et al. Cardiovascular preparticipation screening of competitive athletes: a statement for health professionals from the Sudden Death Committee (Clinical Cardiology) and Congenital Cardiac Defects Committee (Cardiovascular Disease in the Young), American Heart Association. Circulation 1996;94:850.