Topology and dimensions of pig coronary capillary network

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Kassab, Ghassan S., and Yuan-Cheng B. Fung. Topology and dimensions of pig coronary capillary network. *Am. J. Physiol.* 267 (*Heart Circ. Physiol.* 36): H319–H325, 1994.—To provide a morphometric basis for any mathematical modeling of the coronary vasculature, data on the network of coronary capillary blood vessels and the topology of the arteriolar supply and venular drainage relative to the capillaries are presented. The diameters, lengths, and branching patterns of the coronary capillary blood vessels in the right and left ventricles of four pigs were measured. The locations of the coronary arterioles and venules were identified, topological maps were constructed, and the mean functional length of capillaries connecting an arteriole to an adjacent venule was measured. The vasculature was fixed by perfusing the coronary vessels with a catalyzed polymer. After the polymer hardened, plugs of the myocardium were removed, sectioned, dehydrated, and cleared to render the capillary network visible in a light microscope. The capillaries then were traced by optical sectioning. We designated the capillaries as blood vessels of order number zero; we further designated the capillaries as those fed directly by arterioles (C_{0a}), those drained directly into venules (C_{0v}), and those capillary vessels connected to C_{0a} and C_{0v}. The capillaries are connected in patterns identified as Y, T, H, or hairpin and anastomosed through capillary cross-connections (C_{cc}). The C_{cc} vessels may connect adjacent capillaries or capillaries originating from different arterioles. The connection among the capillaries, arteries, and veins is presented in terms of a connectivity matrix. Combining the present data with those for the arterial and venous trees, we have obtained a complete set of statistical data of all the blood vessels of the heart of the pig. Such a data set will serve as the basis of coronary hemodynamics.

heart; capillary cross-connections; morphometry; arterioles; venules; silicone elastomer

TO UNDERSTAND CORONARY CIRCULATION, to predict the pressure-flow relationship, to determine the longitudinal pressure distribution from the coronary artery to the coronary vein, to understand the distensibility of coronary blood vessels, to locate the sites of the waterfall in the coronary waterfall phenomena (or the sluicing gates in the sluicing analogy), to quantitatively determine the process of vascular hypertrophy or remodeling of the coronary blood vessels when hypertension or congestion of flow occurs in the heart, to study atherogenesis or restenosis, and to determine the effect of hypertension, hypertrophy, and tissue remodeling on coronary circulation, one must have the morphometric data of the coronary vasculature (arteries, veins, and capillaries). This is analogous to the need to know the structure of the circuitry as well as the distribution of the resistors, capacitors, and inductors in an electric circuit if one wishes to analyze an electric instrument. Furthermore, to understand the metabolism of the cardiac tissue, the oxygen supply and consumption, the exchange of fluid and ions between blood and tissue, and the distribution of blood flow in the heart one must have the morphometric data of the coronary capillaries because it is in the vasculature that the flow distributes and through the capillary blood vessel walls that the metabolic action and fluid exchange take place. This is analogous to the need to know the chips if one wishes to understand a computer.

Our hypothesis is that the coronary capillaries are not treelike in topology, that a complete set of data suitable for the analysis of blood flow in a whole heart does not exist, and that our method can yield such a set of data. We present in three studies (9, 10, present study) a complete set of data of the pig heart as a basis to investigate the above-named problems. The coronary arteries and endocardial veins are treelike in topology; the coronary capillaries are not. The coronary capillaries form a network with certain special types of connections among its branches and a special three-dimensional relationship with respect to arteries and veins. The numbers, diameters, and lengths of the several types of branches and their spatial connectivity are presented to guide future theoretical modeling of the coronary capillary vasculature.

Morphology of the coronary capillary bed has been the subject of intensive studies in the past century. The first qualitative descriptions of the capillary network were made by Spalteholz in 1907 (20) and then by Nussbaum in 1912 (13). Several years later (in 1928), Wearn (24) developed a method using India ink injections, Formalin fixation, serial sectioning, and light microscopy. Wearn obtained the capillary number-to-muscle fiber number ratio in humans, cats, and rabbits. In 1965, using a modified Wearn technique, Brown (5) described the branching pattern of arterioles, capillaries, and venules of several domestic animals. In 1971, Ludwig (12) injected rabbit hearts and measured their functional capillary length (linear distance between an adjacent arteriole and venule). In 1974, the microfil perfusion method was introduced, which was used by Bassingthwaighte et al. (3) to study capillary morphometry in the left ventricle of the dog. They published data on the capillary diameters, intercapillary distances, segmental and functional capillary lengths, and capillary number densities (3). In the 1980s, scanning electron microscopy of vascular corrosion casts became a popular technique owing to its capability to obtain a three-dimensional view of the microvascular geometry. Publications on the three-dimensional branching pattern of the microvasculature have been reviewed by Anderson et al. (1). Finally, the glutaraldehyde or formaldehyde perfusion-fixation techniques have been used extensively to study the morphometry of the coronary capillaries [see reviews by Anversa and Capasso (2) and Rakusan and Wicker (17)].

These past studies have yielded a wealth of qualitative and quantitative information, but we cannot find a complete set of data suitable for the analysis of blood flow in a whole heart. Using a method of polymer casting, optical sectioning, and computer image analysis, we have studied the vasculature of the pig heart. The present study provides the morphometric data of the capillary network of the pig ventricles. We (9) have given the data of coronary arteries, whereas another study from our laboratory (10) presents those of the coronary veins.

METHODS

Preparation of coronary capillary casts. The hearts of four farm pigs (Yorkshire and Duroc crosses) weighing 30.1 ± 0.7 kg and 3–4 mo of age were prepared by the method reported by us previously (9). In brief, a KCl-arrested, maximally vasodilated heart was perfused with catalyzed silicone elastomer (CP101, Flow Tech.) through its three major coronary arteries and allowed to harden at physiological pressure. A total of 12 plugs of myocardial tissue was removed from each of the left and right ventricles of the four pigs. Each plug was approximately 4 × 4 mm in cross section and extended from epicardium to endocardium. Serial sections of 60–80 μm in thickness were cut from each entire plug. Each section was dehydrated and cleared to render the myocardium transparent and the silicone elastomer-filled microvasculature visible with a light microscope. In total, 148 sections of right ventricle and 117 sections of left ventricle were used to measure the diameter and length of the capillary blood vessels. For measurement of the topology of arteriolar and venular zones in which the capillaries are embedded, however, tissue sections with larger volumes were needed. Hence, additional full-thickness plugs of tissue of approximately 10 × 10 mm in cross-sectional area were taken from one additional pig. The tissue was prepared for histological morphometry using the protocol described above [see Kassab et al. (9) for details].

Measurement of capillary topology and vessel dimensions. We developed an image-processing system, using Data Translation DT2851 software and an IBM-AT computer, to collect data from histological specimens. The microvasculature was viewed with an inverted light microscope (Olympus, resolution of 0.6 μm at ×600 magnification) and displayed on a video monitor (Sony Trinitron Color Video Monitor) through a television camera (COHU Solid-State Camera). The image is grabbed by the computer software and analyzed with a digitizing system. The capillaries were traced, along with their arterioles and venules, by the method of optical sectioning. The diameter and length of each capillary vessel segment (defined as a vessel between successive nodes) were measured.

Distinction of capillaries from arterioles and venules. The capillary network is connected to arterioles and venules. Capillaries fed directly by arterioles shall be called "arterial capillaries," and those drained directly by venules will be called "venous capillaries." Three criteria were used to distinguish arterial capillaries from the arterioles. *1*) Muscle fiber orientation: most capillaries are oriented in the direction of the muscle fiber. *2*) Tortuosity: arterioles are tortuous, whereas capillaries are smooth and nearly straight. *3*) Capillary topology: the branching pattern of the capillaries shown in Fig. 1 is very different from the branching pattern of arterioles (see Ref. 9). *Criteria 1* and *3* can also be used to distinguish venous capillaries from venules. *Criterion 2*, however, cannot be used for venous capillaries because venules are not tortuous, but they can be recognized as described below.

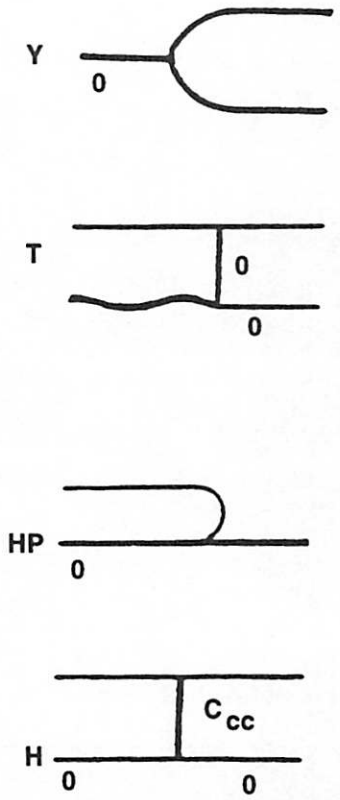

Fig. 1. Schematic diagram of capillary segment branching showing typical geometric patterns known as Y, T, HP (hairpin), and H types. 0, Capillaries of order 0; C_{cc}, capillary cross-connection (like the middle bar of the letter H).

Recognition of arterioles and venules. Coronary arterioles branch off at almost right angles from the small arteries and take either an oblique course to the nearest capillary bed or a winding course to the capillaries of a more distant muscle fiber. The branching pattern of coronary venules (10) is very different from that of arterioles (9). A group of the smallest venules usually draining a capillary bed lie in a plane that is either parallel or transverse to the capillaries and then break away from their original direction and run obliquely toward a larger vein. The characteristic branching pattern of endocardial venules has been referred to as the turnip-root pattern, the ginger-root pattern, or as fingers collecting into a hand (10). The diameter of a coronary venule has a tendency to fluctuate along its length, unlike an arteriole, which has a fairly constant diameter in each segment. Three, four, or even five coronary venules often converge into one at the same point, like a sinus.

Classification of types of nodes and assignment of order numbers to capillary branches. The coronary capillary branches intersect in several nodal patterns, illustrated in Fig. 1. The nodes are classified into four types, namely, Y, T, H, and hairpin (HP) based on their geometric shape. Because arteries are given order numbers 1, 2, 3,... according to their diameters and veins are given the order numbers −1, −2, −3,..., we shall give capillaries an order number of 0. As mentioned above, a capillary between two successive nodes is called a segment. Segments attached to arterioles (arterial capillaries) are designated as C_{0a} vessels, where subscript a indicates artery. Segments attached to venules (venous capillaries) are designated as C_{0v} vessels, where subscript v indicates vein. The C_{0a} and C_{0v} capillary vessels branch further in patterns shown in Fig. 1. We designate the large number of other capillary

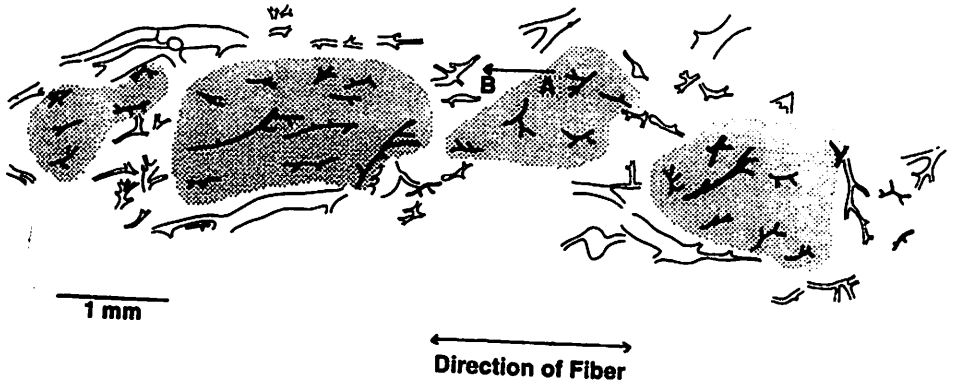

Fig. 2. Reconstructed spatial distribution of arterioles and venules from a histological section taken 1.7 mm from the epicardial surface of right ventricle. Solid vessels, arterioles; open vessels, venules. Shaded regions, arteriolar zones ("islands"); unshaded regions, venular zones ("ocean"). *A* and *B* indicate origin in the arteriolar zone and ending in the venular zone, respectively, of a vessel. See METHODS, *Definitions of mean functional capillary length and mean capillary blood path length*, for details.

segments that connect to C_{0a} and C_{0v} as C_{00} vessels. Some C_{00} capillary segments appear to be extensions of C_{0a} or C_{0v} connected in series. Other C_{00} vessels anastomose in H-type nodes with a segment of cross-connection similar to the middle bar of the letter H; these cross-connections are designated as C_{cc} vessels. The C_{cc} segments may connect two adjacent capillaries or two capillaries further apart (sometimes even from two different arterioles).

Connectivity matrix. All C_{0a} capillaries are connected to coronary arteries but not necessarily to the smallest arterioles (Strahler order 1). Some are connected to order 2 arteries and some to even larger arteries of orders 3 and 4. The statistical data of the average number of capillaries originating from an arterial element of order n (which is composed of segments of the same order connected in series) can be listed as a row matrix $\mathbf{C}(0,n)$. Similarly, a row matrix describing the connection between capillaries and venous elements is defined. These row matrices have the same character as the connectivity matrices $[\mathbf{C}(m,n)]$ of the arteries and veins (9, 10).

Topology of arteriolar and venular zones in myocardium. The trunks of the arterial and venous trees are separated and easily identified in a cast. When the branches divide repeatedly and become smaller and smaller, do the small twigs tend to be distributed uniformly in space? Furthermore, do the twigs of the arterial trees (arterioles) and venous trees (venules) intermingle and both distribute uniformly in space? These questions are important when we want to know how long the paths of blood are between an arteriole and a venule (i.e., the effective length of capillary blood vessel linking an arteriole to a venule). The path length of blood flow in capillaries is an important parameter in determining the resistance to blood flow in the capillaries, which in turn determines the longitudinal distribution of blood pressure in the coronary blood vessels.

To answer these questions, we must study the spatial distribution of the C_{0a} and C_{0v} segments. If the C_{0a} and C_{0v} vessels are uniformly intermingled and uniformly distributed in space, then the effective capillary blood path length between arterioles and venules can be as short as the average segmental capillary length. If the C_{0a} and C_{0v} vessels are segregated to different regions of space, then the effective capillary length between arterioles and venules can be much longer than the average segmental length. An investigation concerning blood flow in the lung by Sobin et al. (19) revealed the latter answer: segregated. For coronary blood flow, these questions require further investigation.

Our study is based on the principle of stereology: certain geometric features of a random aggregation of bodies in a three-dimensional space can be recognized from random-plane cross sections of the aggregates and from the intercepts of straight lines intersecting the aggregates. In a plane cross section of the myocardium, one can identify arterioles and venules. If a cross section of an arteriole is found to have two neighboring arterioles and the triangular area defined by the three cross sections as vertices contains no venules, then the three arterioles lie in an arteriolar zone. Probing arteriolar cross sections in its neighborhood, we can obtain a connected region in which all noncapillary blood vessels are arteriolar, and beyond its border are venules. A similar treatment can be initiated with a venule. The principle of stereology then translates the features recognized in the plane cross sections to the three-dimensional space of the heart.

The purpose of this exercise is to determine the topological structure of the arteriolar and venular zones of the myocardium. If we shade the arteriolar zones while leaving the venular zones without shade, we will obtain a two-colored map. But a two-colored map can represent only islands in an ocean. Hence the topological question is, Which is the ocean? Which are the islands? After this is decided, stereological methods will enable us to determine the size and shape of the islands and the ocean.

Definitions of mean functional capillary length and mean capillary blood path length. An overriding characteristic of the coronary capillaries is that most of them are parallel to the muscle fibers. Therefore, a capillary originating from a point in an arteriolar zone will carry blood to a point in the venular zone in a flow that is parallel to the muscle fiber. An actual reconstructed case is shown in Fig. 2, in which the muscle fibers are horizontal. The ocean (venular zone) surrounding the islands (arteriolar zone) appear as nonoverlapping regions, each of which lies in an immediate neighborhood of an island. *Capillary blood vessel AB* has an origin *A* in an island and an ending *B* in the ocean next to that island. If we assume that every point in the island has an equal chance of being the point *A*, and that every point in the ocean in a direction parallel to the muscle fiber has an equal chance of being point *B*, then the average length of the *capillaries AB* is exactly one-half of the average length of the straight-line segments intercepted by the island and its immediate ocean. In actual collection of data we

Table 1. *Segment diameters and lengths of pig coronary capillaries in RV free wall*

Capillary Order	Diameter *n*	Diameter, μm	Length *n*	Length, μm
C_{0a}	715	6.5 ± 1.0	231	55.4 ± 40.3
C_{00}	764	6.0 ± 1.1	143	62.5 ± 41.2
C_{0v}	322	6.9 ± 1.2	28	47.5 ± 29.5
C_{cc}	210	5.7 ± 1.3	90	33.4 ± 28.3

Values are means ± SD; *n*, no. of vessels measured. RV, right ventricle. All capillaries are order 0: C_{0a}, those fed directly by arterioles; C_{0v}, those drained directly into venules; C_{00}, those connecting C_{0a} and C_{0v} vessels; C_{cc}, capillary cross-connection.

Table 2. *Segment diameters and lengths of pig coronary capillaries in LV free wall*

Capillary Order	Diameter n	Diameter, μm	Length n	Length, μm
C_{0a}	698	6.2 ± 1.1	222	52.0 ± 32.3
C_{00}	764	5.7 ± 1.2	161	54.5 ± 43.0
C_{0v}	414	7.0 ± 1.2	34	45.0 ± 30.5
C_{cc}	210	5.5 ± 1.4	86	21.1 ± 15.5

Values are means ± SD; n, no. of vessels measured. LV, left ventricle.

measure a linear distance between the centers of mass of adjacent arteriolar and venular domains of a capillary bed. The average value of these measurements is defined as the mean functional capillary length.

The theoretical mean functional capillary length is the length of a straight line. The actual capillaries are curved. In the histological specimens we can trace the actual curved lengths of the capillaries from their arterial origins to their venous endings. We define this quantity as the mean capillary blood path length. The ratio of the curved length of a capillary blood vessel to the straight-line functional length of the capillary is a useful quantity for mathematical modeling.

RESULTS

Pattern of pig coronary capillary network. The simplest and the most important observation to make is that the pig coronary capillary network is not treelike. This is in sharp contrast to the topological structure of coronary arteries and endocardial veins, which are indeed treelike (9, 10). The topology of the coronary capillary network consists of preferentially oriented branching tubes with cross-connections along their length. The coronary capillaries branch and intersect in several patterns (H, Y, T, or HP). The relative frequencies of H, Y, T, and HP types in the right ventricle of the pig are 0.52, 0.21, 0.21, and 0.06, respectively, whereas those in the left ventricle of the pig are 0.53, 0.21, 0.20, and 0.06, respectively.

Tables 1 and 2 summarize the morphometric data of the capillaries in the right and left ventricular free walls, respectively. The statistical data from four pigs are lumped together. The means ± SD of the capillary segment diameters and lengths and the number of observations are shown for C_{0a}, C_{0v}, C_{00}, and C_{cc}.

The distances between each pair of consecutive C_{cc} vessels along the capillaries were found to be 61.2 ± 44.0 (n = 54) and 52.9 ± 39.6 (n = 57) μm for right and left ventricles, respectively.

We examined the variability among the four animals by analyzing the statistical morphometric data from each heart separately. The morphometric results on the diameters from the four hearts were similar. Hence, the data were lumped together for the final statistics, shown in Tables 1 and 2.

Connection of capillary network to arterioles and venules. The connectivity of blood vessels of one order to another is given by the connectivity matrix $\mathbf{C}(m,n)$ (9). The connectivity data are presented in the form of a matrix, the component of which in row n and column m is the ratio of the total number of elements of order n sprung off from elements of order m to the total number of elements in order m. The connectivity matrices of the three coronary arterial trees (right coronary artery, left anterior descending coronary artery, and left circumflex coronary artery) are given in our previous work (9). The connectivity matrices of the coronary sinusal and thebesian veins have also been constructed (10). The connectivity of the C_{0a} and C_{0v} vessels to the arterial (right and left ventricular) and venous (sinusal and thebesian) trees is shown in Table 3. For example, a single right ventricular arteriolar element of order 1 gives rise to an average of 2.75 capillaries. Similarly, single right ventricular elements of orders 2, 3, and 4 give rise to an average of 0.674, 0.151, and 0.40 capillaries, respectively. No capillaries arise from arterial vessels of orders greater than 4.

The total number of capillaries arising from each of the coronary arteries can be computed from information given in Table 3 and the APPENDIX of Kassab et al. (9). The total numbers of arterial capillaries arising from the right coronary artery, left anterior descending coronary artery, and left circumflex artery is 1,187,179 ± 515,552, 1,273,281 ± 813,674, and 516,084 ± 332,019, respectively. The total number of arterial capillaries in a whole heart weighing 155 g is 3,018,384 ± 1,697,777. The total number of venous capillaries can also be computed from Table 3 and results of Kassab et al. (10). The total number of venous capillaries in the same whole heart is 5,085,977 ± 2,085,250.

Topology of arteriolar and venular zones and functional and path length of capillaries. Our topological study of the arteriolar and venular zones has yielded the result that, in plane cross sections (Fig. 2), the arteriolar

Table 3. *Connectivity of C_{0a} and C_{0v} to arteries and veins in RV and LV*

	Order Number							
	1	2	3	4	5	6	7	8
Coronary arteries (C_{0a})								
RV	2.75 ± 0.082	0.674 ± 0.067	0.151 ± 0.045	0.040 ± 0.028				
LV	3.18 ± 0.118	0.675 ± 0.080	0.148 ± 0.081	0				
RV and LV coronary veins (C_{0v})								
Sinusal	2.56 ± 0.073	0.426 ± 0.068	0.347 ± 0.067	0.033 ± 0.008	0.012 ± 0.003	0.020 ± 0.007	0.006 ± 0.003	0
Thebesian	2.56 ± 0.073	0.426 ± 0.068	0.347 ± 0.067	0.067 ± 0.011	0.015 ± 0.005	0.020 ± 0.008	0.014 ± 0.010	0.020 ± 0.020

Values are means ± SE of capillaries given out by each artery or vein of a specific order.

Table 4. *Capillary diameters in LV and RV of various species*

Species	Region	Diameter, μm	Method	Reference
dog	LV	5.5 ± 1.3	microfil perfusion	(3)
dog	LV	6.3 ± 0.6	diastole, in vivo	(22)
rat	LV	5.3 ± 1.4	anoxic, arrested	(8)
rat	LV	6.0 ± 1.0	control, in vivo	(21)
		6.4 ± 0.3	hypoxia, in vivo	
rat	LV, endo	5.1 ± 0.1*	glutaraldehyde fixation	(6)
	LV, epi	3.8 ± 0.1*		
dog	LV, endo	4.4 ± 0.1*	glutaraldehyde fixation	(7)
	LV, epi	4.5 ± 0.1*		
rat	LV	6.5 ± 0.2*	acetone fixation	(18)
	RV	5.8 ± 0.5*		
rat	LV	5.1 ± 1.4	SEM + corrosion	(16)
human	LV	5–7	SEM + corrosion	(14)
rat	LV, subendo	6.9 ± 1.7	frozen sections	(11)
rat	LV, subepi	4.9 ± 0.3*	glutaraldehyde fixation	(15)
	LV, subendo	4.5 ± 0.2*		
pig	RV	6.0 ± 1.1	glutaraldehyde fixation	(25)
pig	RV, C_{0a}	6.5 ± 1.0	silicone elastomer	Present study
	RV, C_{00}	6.0 ± 1.1		
	RV, C_{0v}	6.9 ± 1.2		
	RV, C_{cc}	5.7 ± 1.3		
	LV, C_{0a}	6.2 ± 1.1		
	LV, C_{00}	5.7 ± 1.2		
	LV, C_{0v}	7.0 ± 1.2		
	LV, C_{cc}	5.5 ± 1.4		

Values are means ± SD except where noted (*mean ± SE). Endo and epi, endocardium and epicardium, respectively; SEM, scanning electron microscopy.

zones are islands and the venular zone is an ocean. We measured the mean capillary path length by tracing the capillary pathway from an arteriole to a venule, the results of which were 547 ± 228 (n = 8) and 550 ± 203 (n = 8) μm for right and left ventricles, respectively. We also measured the functional mean capillary length as a linear distance between the center of mass of two adjacent arterial and venular domains, the results of which were 501 ± 178 (n = 189) and 512 ± 163 (n = 193) μm for right and left ventricles, respectively. The ratios of the two measurements are ~1.09 and 1.07 for right and left ventricles, respectively. These data suggest that most capillary pathways followed the shortest path from terminal arteriole to collecting venule.

The above data show that the functional length and path length of capillaries between arterioles and venules are much longer than the capillary segmental lengths shown in Tables 1 and 2. The path length-to-segment length ratio is between 8 and 10. To more clearly define this concept, we may consider the expected number of cross-connecting capillaries (N_{cc}), the C_{cc} segments, in a single path between an arteriole and a neighboring

Table 5. *Capillary segmental and functional lengths in LV and RV of various species*

Species	Region	Segmental Length, μm	Functional Mean Length, μm	Method	Reference
rabbit	LV, subepi		400 (380–460)	india ink perfusion	(12)
	LV, intramural		300 (200–380)		
	LV, subendo		500		
	RV, subepi		400 (350–480)		
	RV, intramural		400 (320–540)		
	LV, subendo		500		
rat	LV	65	310 (100–800)	dye-suspension perfusion	(23)
cat	LV	110	400		
dog	LV	100	500–1,000	microfil perfusion	(3)
rat	LV	95 ± 3*	593 ± 15	frozen and stained	(4)
		75 ± 2†			
pig	RV, C_{0a}	55.4 ± 2.6	501 ± 12.9	silicone elastomer	Present study
	RV, C_{00}	62.5 ± 3.4			
	RV, C_{0v}	47.5 ± 5.6			
	RV, C_{cc}	33.4 ± 3.0			
	LV, C_{0a}	52.0 ± 2.2	512 ± 11.7		
	LV, C_{00}	54.5 ± 3.4			
	LV, C_{0v}	45.0 ± 5.3			
	LV, C_{cc}	21.1 ± 1.7			

Values are means or means ± SE. *Arteriolar segment length; †venular segment length.

venule. Let the distance between a pair of consecutive C_{cc} vessels be denoted as $L_{cc\text{-}cc}$. Then, the ratio of the mean capillary path length ($L_{a\text{-}v}$) to $L_{cc\text{-}cc}$, that is

$$N_{cc} = \frac{L_{a\text{-}v}}{L_{cc\text{-}cc}} - 1$$

is the average number of C_{cc} vessels in a single path. If $L_{a\text{-}v}$ and $L_{cc\text{-}cc}$ have standard errors $\delta L_{a\text{-}v}$ and $\delta L_{cc\text{-}cc}$, then the fractional propagated error in N_{cc} can be expressed as

$$\frac{\delta N_{cc}}{N_{cc}} = \frac{\delta L_{a\text{-}v}}{L_{a\text{-}v}} + \frac{\delta L_{cc\text{-}cc}}{L_{cc\text{-}cc}}$$

with the values of $L_{a\text{-}v}$ and $L_{cc\text{-}cc}$ given above, the calculated N_{cc} and its propagated error are 8 ± 2 and 9 ± 2 for the right and left free ventricular walls, respectively.

DISCUSSION

In the present study, capillaries are defined as the smallest coronary blood vessels that do not obey the treelike topology of the arteries and endocardial veins. In the literature, capillary blood vessels are defined as *1*) vessels of the smallest diameter and *2*) vessels without vascular smooth muscle. Our definition leads to these same vessels.

There is a wealth of data in the literature on the diameter of the capillaries. Table 4 provides a comparison of the present data with those reported previously. In many prior studies, the upper boundaries of the diameter range of the capillaries are defined arbitrarily. In the present study, the upper boundaries are defined by the topological boundaries between treelike and networklike zones of vasculature, and the branches of the capillary network are separated into four categories: C_{0a}, C_{00}, C_{0v}, and C_{cc} vessels. If we lump all four categories together, then we get 6.3 ± 1.2 (SD) (n = 2,011) and 6.1 ± 1.2 (n = 2,086) μm for the diameters of the capillaries in the right and left ventricles of the four pig hearts. These numbers are not very different from those in the literature observed in vivo, suggesting that the species differences are not large. However, the data in Table 4 obtained by perfusion fixation method show smaller capillary diameters than ours, which may be due to fixation shrinkage.

We introduced the concept of a connectivity matrix, whose element in the mth row and nth column is the average number of vessels of order m branched off from a vessel of order n. We have determined the values of the elements of the connectivity matrix of the entire vascular tree, including the arteries, veins, and capillaries. The capillaries are connected to the arterial tree with C_{0a} and to the venous tree with C_{0v} vessels.

The coronary capillaries are connected together into a network that perfuses a three-dimensional space. We classified the nodes of this network into four categories: Y, T, H, and HP. The most interesting is the H type, which contains a C_{cc} and allows the fluid in the two longer parallel vessels to communicate. We have determined the size, number, and spacing of the C_{cc} vessels. The presence of C_{cc} vessels in the myocardial capillaries may serve several functions: they may make the pressure distribution in the capillary bed more uniform, they may play a role in oxygen transport if countercurrent flows prevail in coronary capillaries, and they may serve as mechanical supports of the capillaries during ventricular contraction. For these reasons the C_{cc} vessels must be taken into account when modeling the hemodynamics of the capillary bed.

There is also a wealth of data on the length of the capillaries. Table 5 summarizes the data on the mean segmental length and the functional mean capillary length (length of blood flow pathway from an arteriole to an adjacent venule) of the coronary capillaries in the ventricles of various species. To compare our results on the capillary segment length with those in the literature, we must lump together the capillary lengths of C_{0a}, C_{00}, and C_{0v} vessels. The results are 57.8 ± 40.4 (n = 402) and 52.7 ± 36.9 (n = 417) μm in the right and left ventricles of the four pig hearts, respectively. Our results are smaller than those reported for other species, see Table 5, suggesting the existence of species differences. However, one explanation may be that the other studies did not take into account the lengths of the T-type capillaries. Those capillaries are transverse to the fiber direction and are usually much shorter than those capillaries that run parallel to the fiber direction; their inclusion will reduce the mean value of the capillary segment length.

The topology of the arterial and venous zones in the myocardium has turned out to be similar to those of the lung (19). This is not surprising but is useful to know.

With the morphometric data presented in these studies, equivalent circuits of the vasculature can be constructed that are consistent with the statistical data. Hemodynamic analysis can be done for a specific circuit or for a selected set of special circuits, all of which are realistically based on the anatomy of the animal.

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