

C. Futami · K. Tanuma · Y. Tanuma · T. Saito

The arterial blood supply of the conducting system in normal human hearts

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Abstract The distributing artery of the conducting system of the heart is occasionally injured in cardiac surgery. The aim of this study was to define the anatomic characteristics of the principal arterial source of the sinu-atrial node and atrioventricular node. Furthermore, the morphology of the tendon of Todaro was clarified. Thirty hearts were studied by gross anatomic methods, and the exact area of the conducting system was supported by histologic observations of four hearts. The sinu-atrial node was supplied by the right coronary artery more frequently (73% of cases) than by the left (3%), and in 23% of cases this node was supplied by both coronary arteries. The atrioventricular node was supplied by the right coronary artery (80% of cases) more than by the left (10%), and in 10% of the cases this node was supplied by both coronary arteries. The atrioventricular bundle branch arose from the right coronary artery in 10% of cases, the left coronary artery in 73%, and both coronary arteries in 17%. Most of the blood to the right bundle (the moderator band) was supplied by the interventricular septal branches of the anterior interventricular branch from the left coronary artery. Finally, all the arteries of the right bundle and left bundle were defined to be derived from left coronary arteries.

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La vascularisation artérielle du système cardionecteur du cœur humain normal

Résumé Il arrive parfois que la vascularisation artérielle du système cardionecteur soit blessée au cours de la chirurgie cardiaque. Le but de ce travail était de définir les caractéristiques anatomiques des principales sources artérielles pour les nœuds sinu-atrial et atrio-ventriculaire. De plus, nous avons clarifié la morphologie du tendon de Todaro. Trente cœurs ont été étudiés par les techniques d'anatomie macroscopique et la localisation exacte du système cardionecteur a été vérifiée par une étude cytologique sur quatre cœurs. Le nœud sinu-atrial était vascularisé par l'artère coronaire droite plus souvent (73% des cas) que par la gauche (3%) et, dans 23% des cas, il était vascularisé par les deux artères coronaires. Le nœud atrio-ventriculaire était vascularisé plus souvent par l'artère coronaire droite (80% des cas) que par la gauche (10%) et, dans 10% des cas, il était vascularisé par les deux artères coronaires. Le rameau destiné au faisceau atrio-ventriculaire naissait de l'artère coronaire droite dans 10% des cas, de l'artère coronaire gauche dans 73% des cas et des deux artères coronaires dans 17% des cas. L'essentiel de la vascularisation de la branche droite ("moderator band") était fourni par les rameaux septaux interventriculaires du rameau interventriculaire antérieur de l'artère coronaire gauche. Enfin, toutes les artères destinées aux branches droite et gauche dérivait de l'artère coronaire gauche.

Keywords Coronary artery · Conducting system · Sinu-atrial nodal branch · Atrioventricular nodal branch · Septomarginal trabecula · Tendon of Todaro

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C. Futami (✉) · K. Tanuma · T. Saito
Department of Anatomy,
Nippon Medical School, 1-1-5 Sendagi,
Bunkyo-ku, 113-8602, Tokyo, Japan
E-mail: brian@nms.ac.jp
Tel.: +81-3-38222131
Fax: +81-3-56856640

Y. Tanuma
Department of Anatomy,
Teikyo University School of Medicine, Tokyo, Japan

Introduction

Although there are a number of descriptions [1, 3, 5, 7, 9, 17, 18] of the artery of the conducting system of the

heart, rarely have papers been written about the arterial vascularization in serial sections of the conducting system. We studied the origin and course of the sinu-atrial and atrioventricular nodal branches, and the arterial blood supply of the atrioventricular bundle, right bundle and left bundle in serial samples. Taking into account the course and mode of termination, we classified the blood supply patterns of the conducting system of the heart in order to develop a useful tool for planning cardiac surgery. The results of this study are expected to help to minimize accidental ablations of the cardiac conducting system during intracardiac repair.

Materials and method

The specimens used for this investigation were hearts removed from 30 cadavers with ages at death ranging from 53 to 97 years. The hearts were fixed in 10% formaldehyde solution for more than 3 months. Latex rubber mixed with a red (naphthol crimson) or blue (ultramarine blue) pigment (acrylic polymer emulsion) was injected into the coronary arteries through their aortic orifices using injection-corrosion technique. Red latex rubber was injected into the left coronary artery and blue into the right coronary artery. First, we traced the coronary arteries and their branches by removing the epicardium gross anatomically or sometimes with the aid of a stereomicroscope. Furthermore we made use of histologic observations [11] of four hearts for the identification of the area of the conducting system as reference materials. Then, we clarified the route of the artery of each part of conducting system in the heart. Technical terms employed followed the Terminologia Anatomica [6].

Results

Sinu-atrial nodal branch

The sinu-atrial node was located near the terminal groove of the right atrium just below the superior vena cava (Fig. 4) [19]. Fig. 1 shows the original position of

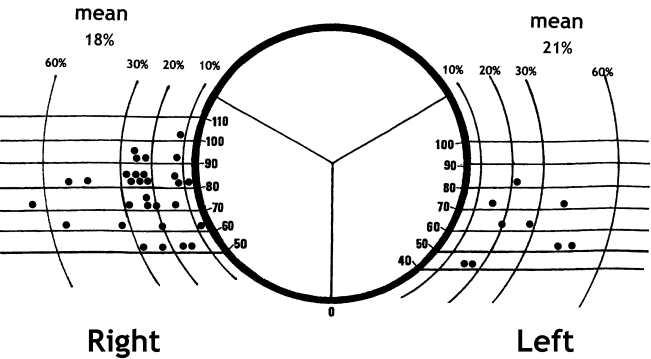


Fig. 1 Original position of the sinu-atrial nodal branch with the distance plotted between the origin of the sinu-atrial nodal branch and its relevant coronary orifice. The distance was calculated as a proportion of the circumferential length of the supravulvar ridge. The mean distance between the right origin of the sinu-atrial nodal branch and the coronary orifice was 18% and that of the left origin was 21%

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The sinu-atrial node was supplied by various combinations of its feeding arteries. As shown in Fig. 2, there were 14 types of arterial variations for the sinu-atrial node in 30 specimens. The sinu-atrial nodal branch arose from the right coronary artery in 29 specimens (the blue artery in Figs. 2, 3a). It corresponded to a right anterior medial atrial artery (containing types a, b', b'') and right posterior medial atrial artery (containing type e) [4] (Fig. 3b). This artery of type e arose from the distal right coronary artery, running upward to the sinu-atrial node retrocavally. The sinu-atrial nodal branch arose from the left coronary artery in eight specimens (red artery in Figs. 2, 3c). It corresponded to a left superior atrial artery (containing types c, d) and arose from the circumflex branch of the left coronary artery without exception. The sinu-atrial nodal branch ran along the anterior wall of the left atrium, passing under the auricle of the atrium to reach the sinu-atrial node. The total course of the sinu-atrial nodal branch arising from the left coronary artery was rather longer than the course from the right coronary artery. Seven specimens exhibited a bilateral arterial supply of the sinu-atrial node.

We recognized the sino-auricular ring terminating pericavally in nine specimens (the term "sino-auricular ring" was coined by Keith and Flack [12]). There were sinu-atrial nodal branches derived from the sino-auricular ring formed by the right coronary artery in six

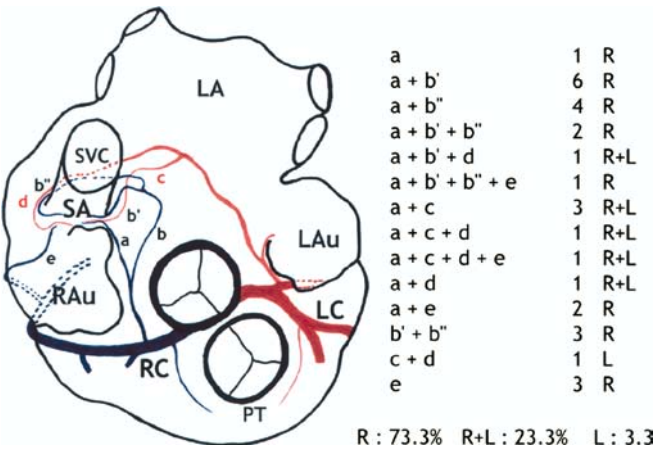


Fig. 2 Arterial supply of the sinu-atrial node, showing 14 types of arterial variations for the sinu-atrial node. R, Percentage of distribution from the right coronary artery; L, percentage of distribution from the left coronary artery; R + L, percentage of distribution from bilateral coronary supply. Blue and red arteries show the right and left coronary arteries respectively. In each type of vascularization, the number of sinu-atrial nodal branches and which artery fed the sinu-atrial node is described on the right-hand side

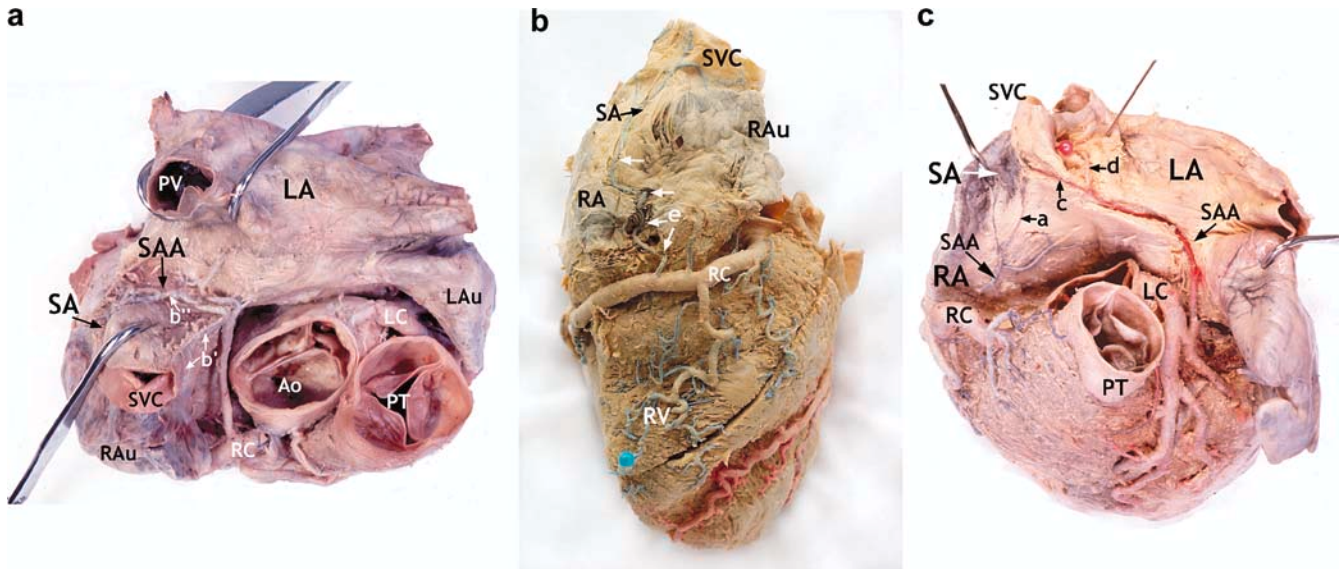


Fig. 3a–c The arterial variation for the sinu-atrial node. **a** Type $b' + b''$; **b** type e (white arrows); **c** type $a + c + d$. *Ao*, aortic valve; *Aov*, aortic sigmoid valvules; *Av*, atrioventricular node; *AVA*, atrioventricular nodal artery; *AVB*, atrioventricular bundle; *Ias*, interatrial septum; *LA*, left atrium; *Lau*, left auricle; *LB*, left branch of the atrioventricular bundle; *LC*, left coronary artery; *LV*, left ventricle; *M*, mitral (left atrioventricular) valve; *Mb*, moderator band; *Mis*, membranous part of the interventricular septum; *Ocs*, ostium of the coronary sinus; *Of*, oval foramen; *P*, *PA*, pulmonary artery; *PT*, pulmonary trunk; *PV*, pulmonary vein; *RA*, right atrium; *RAA*, right atrial artery; *RAu*, right auricle; *RB*, right branch of the atrioventricular bundle; *RC*, right coronary artery; *RV*, right ventricle; *SA*, sinuatrial node; *SAA*, sinuatrial nodal artery; *Seb*, subendothelial branch; *SVC*, superior vena cava; *T*, tricuspid (right atrioventricular) valve

specimens (Fig. 3a) and a sinu-atrial nodal branch likely formed by the left coronary artery in three specimens (Fig. 3c).

In Fig. 4 we show as a reference preparation the histologic observations on the sinu-atrial nodal branches feeding the sinu-atrial node. The sinu-atrial nodal branch is situated in the center of the sinu-atrial node. We recognized the red pigment injected from the left coronary artery in its arterial lumen.

Atrioventricular nodal branch

Position of the atrioventricular node

The atrioventricular node was found in the base of the atrial septum at the apex of the triangle of Koch in all specimens [16, 19]. Thus, before identifying the atrioventricular node, we had to identify “the triangle of Koch”, which was delimited by the atrial orifice of the coronary sinus, the supra-ventricular ridge of the septal cuspid of the right atrioventricular valve and the tendon of Todaro, to dissect its feeding artery. Compared with the coronary sinus and supra-ventricular ridge, it was difficult to identify the tendon of Todaro, because there

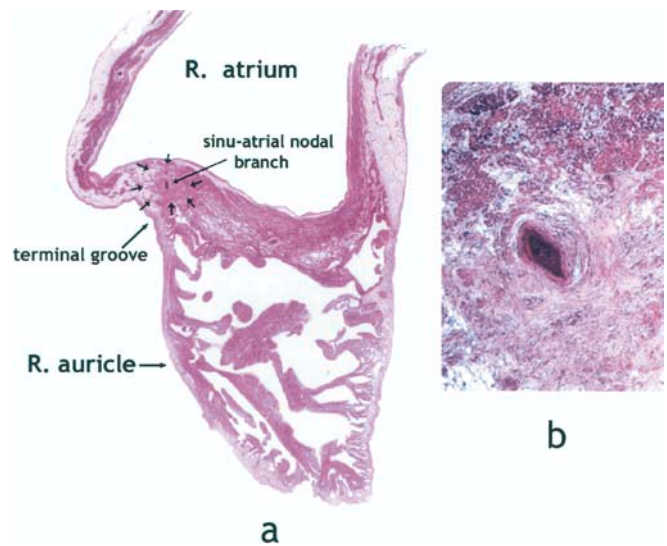


Fig. 4a, b Histologic observation of the sinu-atrial node (HE stain). **a** Semi-macroscopic view of the sinu-atrial node (*SA*) (cross-section of the right atrium). This node is in the terminal groove of the right atrium just below the superior vena cava, encircled by seven small arrows. **b** Magnified ($\times 4$) view of the sinu-atrial node. The tissue of the sinu-atrial node is found as specific myocardial fiber against its peripheral myocardial fiber by pink-colored staining. The sinu-atrial nodal artery (*SAA*) is situated in the center of the sinu-atrial node

were many variations in the morphology and location of this tendon (Fig. 5).

In typical cases, the valve of the inferior vena cava (Eustachius's valve) and the valve of the coronary sinus (Thebesius's valve) met just above the coronary sinus and formed the tendon of Todaro, running toward the central fibrous body. The tendon of Todaro coursed within a superficial layer of the right atrial muscle. The tendon width was 2–3 mm in 15 specimens in which the tendon was clearly dissected, 0.5–1 mm in eight specimens in which the tendon was

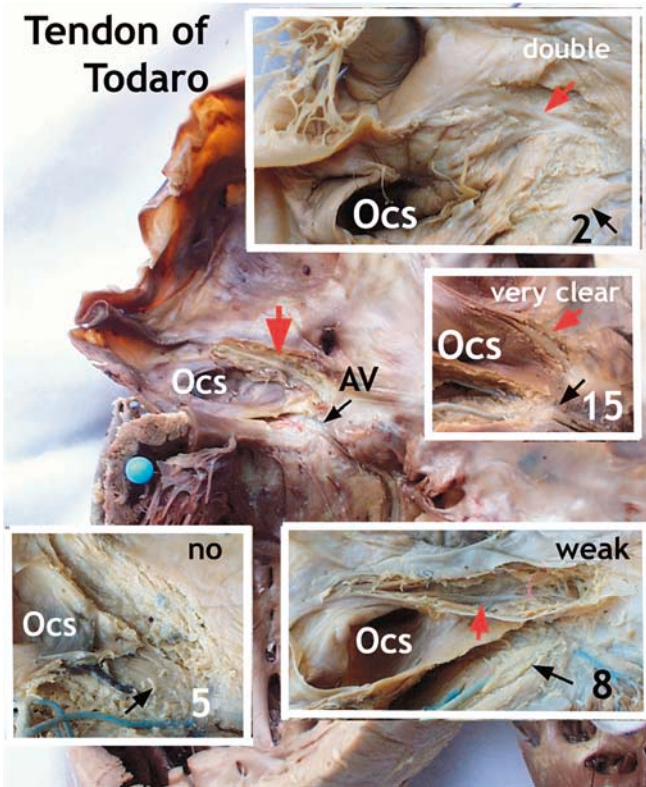


Fig. 5a–d Morphology and location of the tendon of Todaro in four variations. The *red arrow* indicates the tendon of Todaro. The *black arrow* locates the atrioventricular node. **a** Double tendons of Todaro derived from Eustachius's valve and Thebesius's valve in two specimens. **b** Clearly dissected tendon of Todaro, as found in 15 specimens. **c** Poorly formed tendon of Todaro, as found in eight specimens. **d** No tendon of Todaro, as found in five specimens

poorly formed, and could hardly be found in five cases. As a result, we have described four types of variations (Fig. 5).

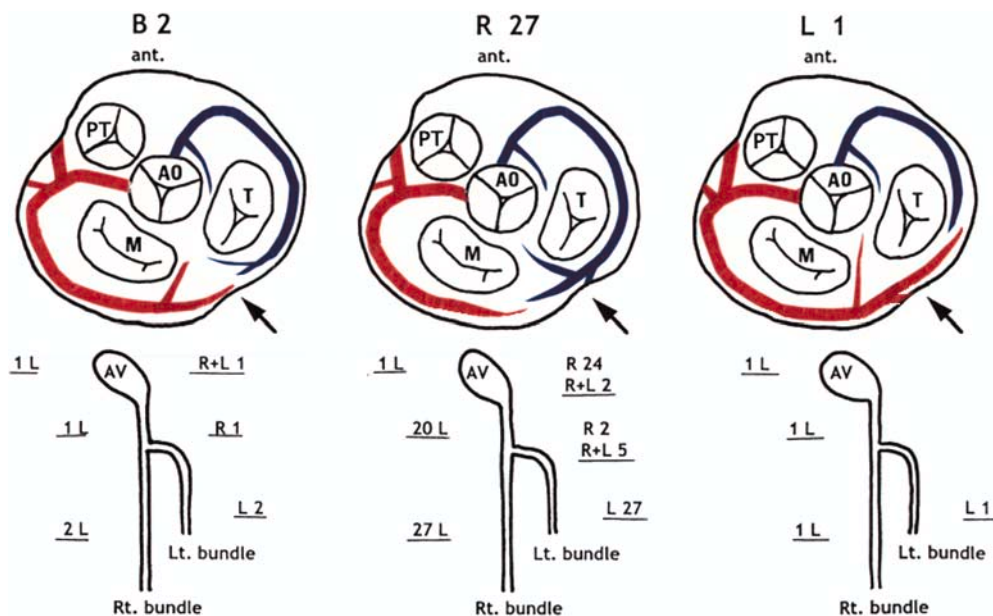
Arterial blood supply of the atrioventricular node

We investigated the relationship between coronary arterial predominance and arterial distribution for the atrioventricular conducting system in 30 specimens (Fig. 6). The 30 specimens were established as having the following coronary arterial dominance [15]: right dominance, 27 specimens (90%); left dominance, one specimen (3%); balanced system, two specimens (7%).

Almost all the atrioventricular nodal branches ran into the myocardium at the posterior-interventricular sulcus and proceeded along the septal margin of the right atrioventricular valve toward the atrioventricular node. After feeding the atrioventricular node, the atrioventricular nodal branch ran directly to the atrioventricular bundle underneath the atrioventricular node (Fig. 7). However, in one case the atrioventricular nodal branch that derived from the sinu-atrial nodal branch ran downward for the atrioventricular node (Fig. 8).

The atrioventricular nodal branch arose from the right coronary artery in 24 specimens (80%), the left coronary artery in three specimens (10%), and both coronary arteries in three specimens (10%) (Fig. 6).

Fig. 6 Relation between coronary arterial predominance and arterial distribution for the atrioventricular conducting system in 30 specimens. *B*, balanced system type; *R*, right dominant type; *L*, left dominant type; *arrow*, posterior interventricular sulcus. The *upper schemes*, are drawings of the superior views of the ventricles of the heart. *Blue* and *red* lines show the right and left coronary arteries. The *lower schemes* show drawings of the arterial distribution for the atrioventricular node, atrioventricular bundle, right and left bundles. *R'*, distribution from the right coronary artery; *L*, distribution from the left coronary artery; *R + L*, distribution from bilateral coronary arteries. The number of arteries distributing for each part of the conducting system is shown by the additional *number* close to the capital letter



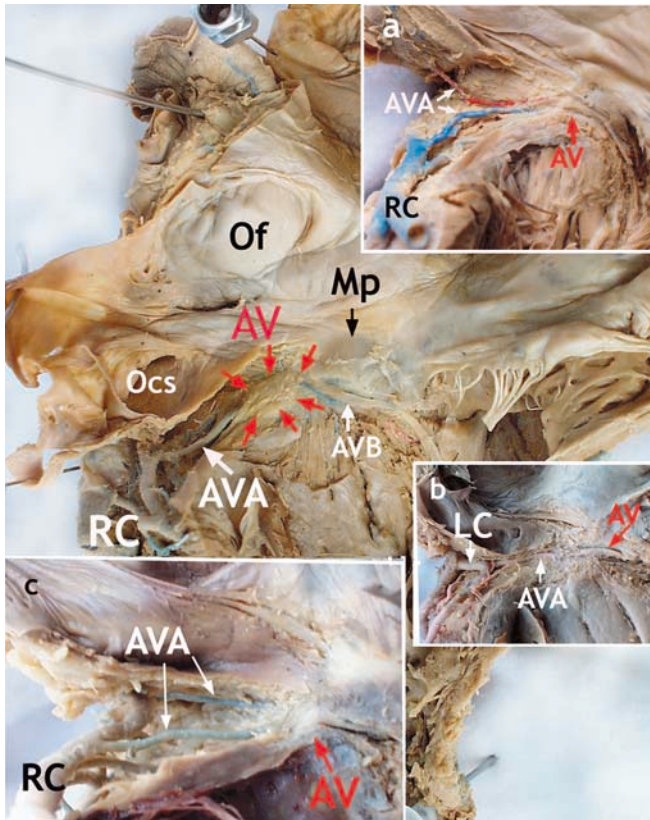


Fig. 7a–c Arterial blood supply of the atrioventricular node (AV) in three variations. The red arrows indicate the atrioventricular node. The right coronary artery (RC) is shown in blue and the left coronary artery (LC) in red. **a** The arterial distribution derived from the bilateral coronary arteries in three specimens. **b** The arterial distribution derived from the left coronary artery in three specimens. **c** The arterial distribution derived from the right coronary artery in 24 specimens

Arterial blood supply of the atrioventricular bundle, right and left bundles

The atrioventricular bundle started from the atrioventricular node, penetrated into the dense connective tissue of the right fibrous trigone and ran down along the membranous part of the interventricular septum. Furthermore, the right bundle and left bundle ramified from the atrioventricular bundle. The right bundle ran down under the endocardium in the moderator band toward the base of the anterior papillary muscle (Fig. 9). After diverging from the atrioventricular bundle, the left bundle passed beneath the membranous part of the interventricular septum to the left ventricle and ramified widely in the left ventricle as subendocardial branches (Fig. 10).

The atrioventricular bundle branch arose from the right coronary artery in three specimens (10%), the left coronary artery in 22 specimens (73%), and both coronary arteries in five specimens (17%) (Figs. 6, 7).

Most of the blood to the right bundle (the moderator band) was supplied by the interventricular septal branches of the anterior interventricular branch from

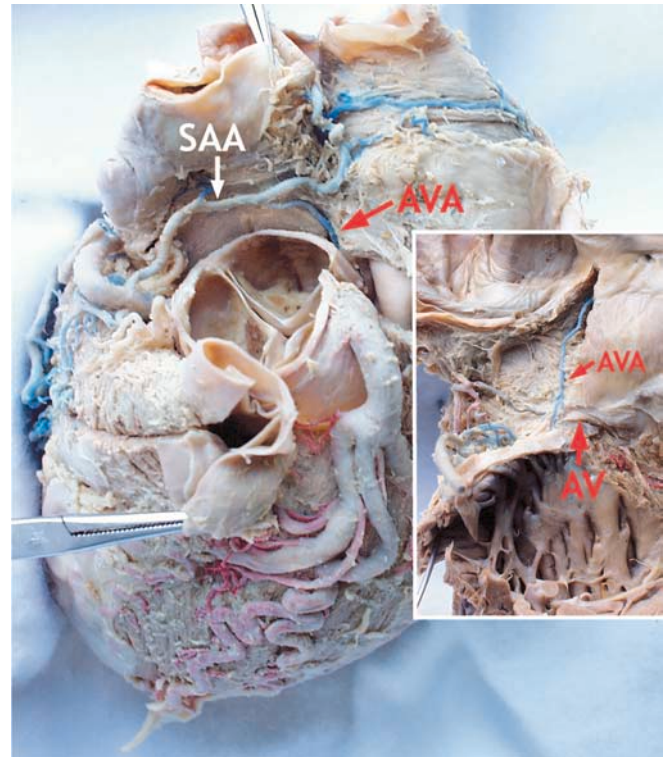


Fig. 8 The atrioventricular nodal branch (AVA) derives from the sinu-atrial branch (SAA) in this specimen. This branch coursed downward for the atrioventricular node (AV). In the right magnified view

the left coronary artery (Fig. 11). The arterial distribution of the right bundle was the same as that of the arterial supply of the moderator band (Fig. 4).

Though the first to fourth interventricular septal branches of the left anterior interventricular branch distributed to the moderator band, the arterial supply of the moderator band originated from the second interventricular septal branch in 33% of cases, and from the first and third branches in 27% (Fig. 11). These branches originated from positions between 16 mm and 48 mm from the orifice of the left coronary artery.

As a consequence, the right bundle was supplied by the interventricular septal branches. Finally, we found all the arteries of the right and left bundles derived from the left coronary artery.

Discussion

Sinu-atrial nodal branch

We have demonstrated the original position of the sinu-atrial nodal branch, displaying the distance between the origin of the sinu-atrial nodal branch and its relevant coronary orifice (Fig. 1). The mean distance between the right origin of the sinu-atrial nodal branch and coronary orifice was 18% of the circumferential length of supra-valvular ridge, while the left origin was 21%. According

Fig. 9a The septal surface of the right atrium and ventricle. The right bundle (*RB*) coursed beneath the subendocardial layer of the moderator band (*Mb*). The *red arrows* indicate the atrioventricular node (*AV*). **b** The septal surface of the right ventricle. Septal branch (*Septal br*) of the left coronary artery (*LC*) penetrates into the moderator band (*Mb*) on the *right-hand* picture. The right bundle (*RB*) penetrates the moderator band; the arterial distribution for this bundle is the same as that of the moderator band

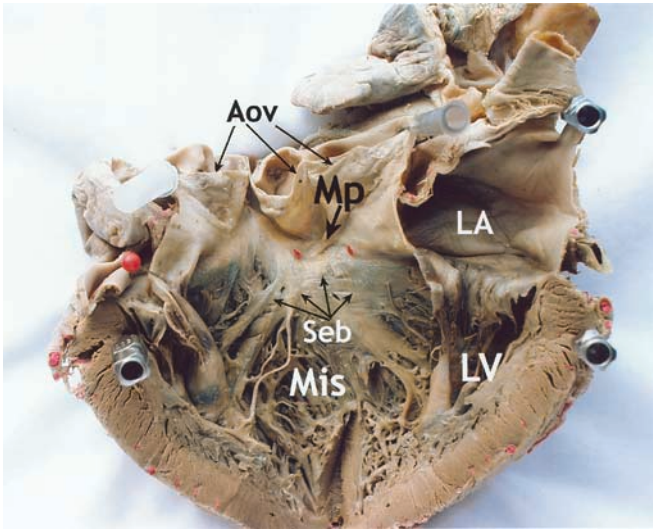
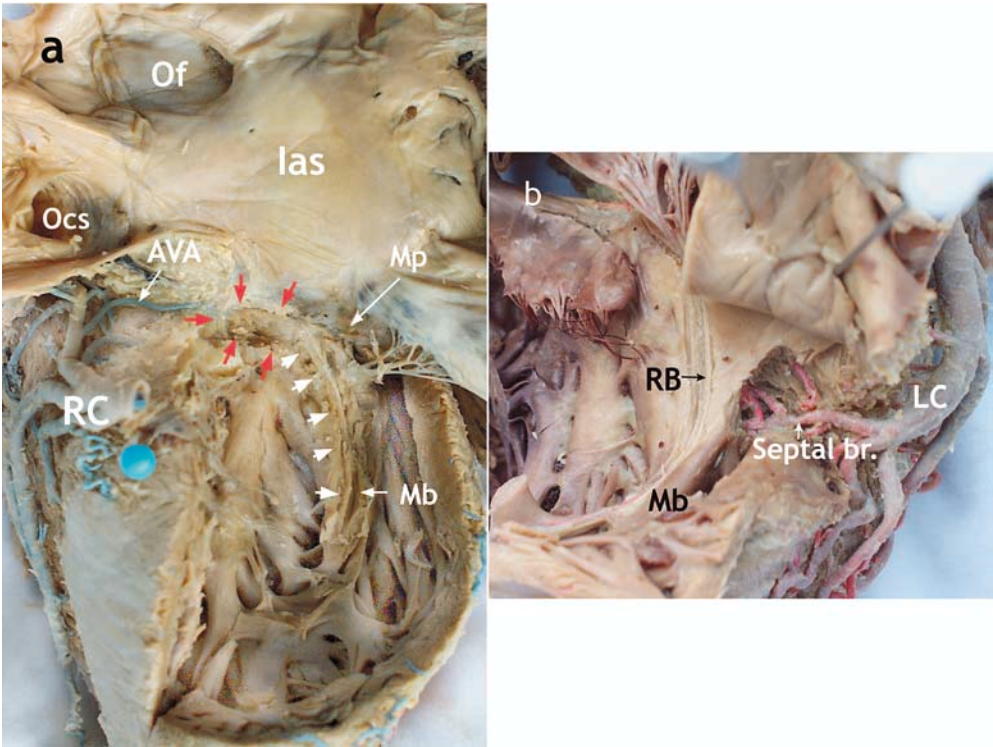


Fig. 10 Interventricular septum observed from the left ventricle. The left bundle passes beneath the membranous part of the interventricular septum (*Mis*) to the left ventricle (*LV*) and ramifies widely in the left ventricle as subendocardial branches (*Seb*). Two *red points* indicate the width of the left bundle

to Busquet et al. [4], who investigated the distance from the right coronary orifice, the average distance is 18 mm. This nearly agrees with our data. Considering the plotted data of Fig. 1, we suggest that the right origin of the sinu-atrial nodal branch is situated more proximally than the left one.

Several authors [4, 5, 8, 10, 17] have reported the vascularization of the conducting systems of the heart.

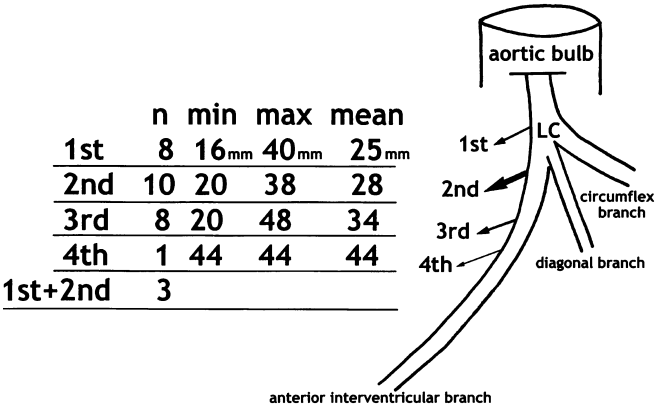


Fig. 11 The first to fourth interventricular septal branches due to the arterial distribution of right bundle. The number of specimens (*n*), and the minimum (*min*), maximum (*max*) and mean (*mean*) of the distance between the origin and the coronary orifice are indicated in each of the interventricular septal branches. *1st + 2nd* shows three specimens distributed from the first and second interventricular septal branches. The arterial supply from the second interventricular septal branch (*bold arrow*) was the most frequent (33.3%)

Recent data are shown in Table 1 and are comparable with our results.

In our specimens, we found a bilateral blood supply for the sinu-atrial node in 23%, but a low percentage of this type of vascularization was noted by other investigators. In particular, DiDio et al. reported that they found only a unilateral blood supply to the sinu-atrial node (Table 1) [5]. In two anatomic textbooks [2, 13], there were no cases showing a bilateral blood supply to

Table 1 Comparison of the origins of the sinu-atrial nodal branch in different studies (CA, coronary artery)

Authors	Right CA	Left CA	Both CA
Busquet J et al. [4]	33 (66%)	15 (30%)	2 (4%)
DiDio et al. [5]	58 (58%)	42 (42%)	0
Sow et al. [18]	29 (64%)	11 (24%)	5 (12%)
Present study	22 (73%)	1 (3%)	7 (23%)

the sinu-atrial node. This difference seems to depend on the technical method used by each investigator [4, 5, 8, 17], for the number of vessels classified as feeding arteries of the conducting system in our study was clearly larger than that found by other authors (Figs. 2, 3). If the other investigators had dissected more precisely, the incidence of a bilateral blood supply might have been larger than the values they reported.

Though it was an artery of type a that supplied the sinu-atrial node most frequently, there were various modes of arterial termination for the sinu-atrial node. This mode of vascularization would compensate for the functional disorder in case of a local coronary infarction.

In nine of 30 specimens (33%) there was a “sino-auricular ring” [4, 8, 12]. According to Busquet et al., the sino-auricular ring is seen in 6% of cases [4]. This mode of vascular termination could be helpful for collateral blood supply in the case of local infarction or surgical incision. This high incidence (33%) might influence the potential for postoperative arrhythmia, recovering from damage caused by artificial cardio-pulmonary arrest during cardiac surgery (Figs. 2, 3).

Extracardiac arteries for nutrition of the sinu-atrial node were found in 1.25% of cases by Hromada [9] and in 12% by Hadziselimovic [7]. However, in the present study we did not investigate the blood supply to the sinu-atrial node originating from arteries other than that given off by the cardiac coronary artery.

Atrioventricular nodal branch

Position of the atrioventricular node [16]

It is clear from the present study that the tendon of Todaro is not always present, but the atrioventricular node is situated at the base of the right atrium at the apex of the triangle of Koch (Fig. 5) [16].

Arterial blood supply of the atrioventricular node

From our data we have developed a unique schema of serial vascularization of each atrioventricular conducting system (Fig. 6). In this schema, we considered the relation between coronary arterial preponderance and arterial distribution for the conducting system [15]. In comparison with variations of the origin of the atrioventricular nodal branch found by the authors in Table 2 [3, 18], the incidence of a right coronary arterial

Table 2 Comparison of the origins of the atrioventricular nodal branch in different studies (CA, coronary artery)

Authors	Right CA	Left CA	Both CA
Sow et al. [18]	32 (84%)	5 (13%)	1 (3%)
Arid et al. [3]	14 (60%)	2 (10%)	7 (30%)
Present study	24 (80%)	3 (10%)	3 (10%)

blood supply for the atrioventricular node in our cases was high [3, 18]. In general, the atrioventricular node is distributed by the right coronary artery [3, 18]. However, we would like to consider the left coronary artery a supplementary feeding artery for the atrioventricular node, referring to the data in Table 2.

Arterial blood supplies of the atrioventricular bundle, right and left bundles

The atrioventricular bundle is thought to form a transitional zone that is supplied from the right and left coronary arteries. That is, this zone is mainly supplied by the right coronary artery on the proximal bundle. But as this zone runs peripherally, the percentage of distribution by the left coronary artery increases gradually.

Regarding the blood supply for right and left bundles, in all cases we found feeding arteries derived from the left coronary artery (Figs. 6, 7, 8, 9, 10, 11). A previous paper described the arterial vascularization of the moderator band [14]. In this paper, Reig et al. emphasized the structural role of the moderator band artery as a collateral circulation route in addition to the perfusion of the right branch of the atrioventricular bundle. This muscular structure involves the right bundle and is distributed by arterial branches which arise from the anterior interventricular artery and perfuse the anterior papillary muscle of the right ventricle. The most frequent source of the moderator band artery in their series was the second interventricular septal artery, as has been observed in this present study. Characteristics of the distribution of moderator band artery in their anatomic study were similar to our data (Figs. 9, 11) [14].

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