ABSTRACT
Anatomy of the conduction system for electrophysiologists is reviewed in two parts. This first part details the historical sequence of discovery of the morphology of the conduction system, current or past issues on the morphology of conduction system and basic anatomy of the conduction system.

Key words: conduction system of heart, arrhythmia, Purkinje network

Introduction
Anatomic substrates of normal or abnormal conduction of electrical stimulation in the heart are far less studied compared to electrophysiologic mechanisms. Studies on the pathology of the cardiac conduction system, summarizing key morphologic features of the major conduction axis and the disposition of the conduction system at a macroscopic level, are still important contents for electrophysiologists. There is a Korean study on the histological findings of conduction systems.

This review illustrates the historical sequence on the understanding of the conduction system and its basic anatomy, after that some questions on the anatomy of the conduction system are formulated. Current understanding of these issues is presented and hypothetical answers are proposed.

Historical sequence of discovery of the conduction system of the heart
The Czech Jan Evangelista Purkynje discovered a net of gelatinous fiber at the sub-endocardium of ventricles in the ungulate heart and published his discovery in Czech in 1839 and in English in 1845. His finding concerned the heart of an ungulate (horse or cow), not a human heart. Little was known about its functional significance and its histological features were strangely interpreted as a kind of cartilage in the heart. Tawara in 1906 was the first to re-discover the significance of Purkinje cells during cardiac contraction. Till now disagreement remains on how to define Purkinje cells or fibers, but it is generally understood that Purkinje cells are vacuolated cells with fast conducting fibers at the atria or ventricular bundle branches.

In 1893, Wilhelm His Jr. from Leipzig discovered the atrio-ventricular bundle (His bundle) and explained the propagation of cardiac contraction through muscle (myogenic conduction) rather than through nerve (neurogenic conduction), which at that time was the dogma. In the same year, A.F. Stanley Kent from Britain also described myogenic conduction independently. Kent described the muscular connection between atria and ventricles as well, but he described several atrioventricular conduction bundles (Kent bundle) in addition to the
His bundle. The nodes and bundles observed by Kent are now understood to be remnants of atrioventricular ring tissue rather than an aberrant connection in the Wolff-Parkinson-White syndrome.

In 1906, Sunao Tawara reported his historical discovery of the AV node in an absolutely perfect description. He was a Japanese physician, who graduated from Tokyo University in 1901 and worked with Ludwig Aschoff in Germany from 1903. His achievements were appreciated by cardiologists not only for his AV node discovery, but also for his integration of previous knowledge about the conduction system by His and Purkinje. Tawara explained how the His bundle expands and how it branches into the left and right bundles as described by Purkinje. One year after Tawara’s discovery, Sir Arthur Keith and his young medical student Martin Flack discovered the sinus node in the heart of several species at an area that histologically resembled the Tawara’s node. In 2007, the centennial discovery of the sinus node by Keith and Flack was celebrated.4,6

Some questions

The historical question “Why does the heart beat?” was answered by Tawara, Keith and Flack.4,6 The next question was on the position of the conduction pathway in a congenitally malformed heart, particularly in the heart with an abnormal looping such as a congenitally corrected transposition.7,8 The expression of ganglion nodosum, which is like an antigen in the conduction system, was discovered by the Amsterdam group during immuno-histochemical studies on the molecular expression of liver.9,10 They realized that tracing the conduction system at the embryonic heart could reveal developmental processes of the human heart. Studies on cell to cell communication like gap junction proteins and on functional development of myofilaments followed.11,12

The development of electro-physiologic techniques to evaluate the mechanism of arrhythmia left the question on the cellular mechanism of the abnormal excitation of the heart10 unanswered. This question is

Figure 1. The septal surface of the right ventricle after removal of the free anterior wall. The His bundle starts from the atrioventricular node (AVN) and runs inferior to the border of the membranous septum (MS) and continues to the right bundle branch (arrows) underneath the medial papillary muscle (MPM) and the septomaginal trabeculation.

CS; orifice of coronary sinus, RCA; right coronary artery, RVO; right ventricular outflow, SEP; septal leaflet of tricuspid valve, VIF; ventriculo-infundibular fold
Figure 2. Left ventricular septal surface and anterior mitral leaflet (AML) after removal of the free wall of left ventricle and mural leaflet of mitral valve. A wedge of fibroadipose tissue interposes at the atrioventricular junction. ALPM; antero-lateral papillary muscle, CS; coronary sinus, LAD; left anterior descending coronary artery, PMPM; postero-medial papillary muscle

recently studied in the pathology of the cardiac conduction system in relation to atrial arrhythmia and some other pathologic heart conditions such as myocardial infarct with arrhythmia.\textsuperscript{13}

One major group of questions left unanswered is about the nature and functional significance of the Purkinje cell.\textsuperscript{14} Purkinje cells are vacuolated cells at the ventricular sub-endocardium found in the ungulate heart. It is agreed upon that they are not seen in the human heart. Some physicians use the term Purkinje fibers, but others talk about Purkinje cardiomyocytes or the Purkinje network. Sometimes, Purkinje cells are referred to as the left bundle branch, but in other occasions a vague term is used describing the peripheral conduction system irrespective of its morphology.\textsuperscript{3}

Basic Anatomy

The landmark of the right ventricular aspect of the conduction axis is documented for surgical anatomy of the heart with ventricular septal defects, which demonstrates its location at the inferior border of the membranous septum of a normal heart (Figure 1), and at the inferior border of hearts with ventricular septal defects of a peri-membranous type. The location of the right bundle branch is also localized at the myocardium underneath the trabecula septomarginalis of the right ventricle.

The left ventricular aspect of the conduction system has a close relation with the anterior mitral leaflet (Figure 2). The left bundle arises from the inferior border of the membranous septum, which lies beneath the non-coronary cusp of the aortic valve and the anterior mitral leaflet. The medial 3/4 of the anterior mitral leaflet is in fibrous continuity with the left cusp and the non-coronary cusp of the aortic valve, but the lateral 1/4 has a free wall where the left atrial and ventricular walls are connected, having a potential for an aberrant connection (Figure 3).

Muscle dissection

Conduction starts from the base of the ventricles and spreads down to the apex, but the contraction starts from the apex so that the ventricles squeeze
Figure 3. Close up of the specimen Fig 2, after lifting up the anterior mitral leaflet to show the aortic valve and the ventricular surface of the mitral anterior leaflet seen from the apex of the left ventricular cavity. Mitral-aortic fibrous continuity is observed between the left and non-coronary cusps and the anterior part of mitral anterior leaflet (dotted line). The posterior part of the mitral leaflet is attached both to the left atrium and left ventricle (line). Arrows indicate the anterior and posterior sub-branches of the left bundle branch.

LC; left coronary cusp, MS; membranous septum, NC; non-coronary cusp, RC; right coronary cusp

Figure 4. After removal of the epicardium and fatty tissue, we can see the direction of cardiac muscle fiber bundles, which make whorls in the apex.

LAD; left anterior descending coronary artery, LV; left ventricle, RV; right ventricle.
from the apex. Dissection of the cardiac muscle at macroscopic level confirms this principle (Figure 4). Then the question arises if the left and right bundle branches form a U-turn at the apex through a counter current of the septal area’s bundle branch and the Purkinje network (Figure 5).

Conclusion

The cardiac conduction system of ventricles consists of the Atrioventricular node, the His bundle and right and left bundle branches. They run to the apex to connect to the peripheral conduction system called ‘Purkinje network’. The histological details and functional molecular nature of the conduction system and Purkinje network will be discussed in part II.

References

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Figure 5. Further dissection of the ventricular septum shows gradual change of their direction. The free wall of the left ventricle has a fiber direction in parallel to the long axis of heart.

