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An Overview on Cardiac Muscle Anatomy, Histology and Embryology

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Abstract:

Cardiac muscle is a specialized type of striated muscle adapted to sustain rhythmic contractions required for effective blood circulation. It exhibits unique structural and histological features that distinguish it from skeletal and smooth muscles. The embryological origin of cardiac tissue highlights its early development and critical role in forming a functional cardiovascular system. This overview provides a concise summary of the anatomy, histology, and embryology of cardiac muscle with emphasis on clinical relevance.

Keywords: Cardiac muscle; Myocardium; Intercalated discs; Histology; Embryology; Cardiogenesis; Anatomy.

Introduction:

Cardiac muscle represents a unique biological tissue with properties essential for sustaining life. Anatomically, the myocardium forms the thick middle layer of the heart wall and is organized to support efficient pumping against systemic and pulmonary circulation demands. Its architecture, including branching fibers and specialized conduction pathways, ensures synchronous contraction across the chambers **(1).**

Histologically, cardiac muscle fibers are characterized by cross-striations, central nuclei, and intercalated discs containing desmosomes, fascia adherens, and gap junctions. These structures enable strong mechanical connections and rapid electrical conduction, which are crucial for maintaining coordinated cardiac output **(2).**

Embryologically, cardiac muscle arises from mesodermal progenitors during early development, with the primitive heart tube forming by the third week of gestation. Subsequent processes of looping, chamber formation, and septation establish the mature heart. Disruptions in these events may result in congenital malformations such as septal defects or abnormal conduction pathways **(3).**

Cardiac Muscle Anatomy, Histology and Embryology:

A- Anatomy of Cardiac Muscle:

Cardiac muscle is an involuntary and striated muscle that constitutes the main tissue of the heart wall. The heart wall consists of three layers enclosed in the pericardium **(Fig.1)**. Epicardium is the outermost layer of the heart wall formed by the visceral layer of the pericardium, surrounds the cardiac muscle on the exterior and protects it from contact with other organs. Myocardium is the thick middle layer of the heart wall that allows the heart chambers to contract and relax to pump blood throughout the body. Endocardium is the inner layer that constitutes the lining endothelium of the myocardium from inside and separates it from the blood within the chambers of the heart **(4)**.

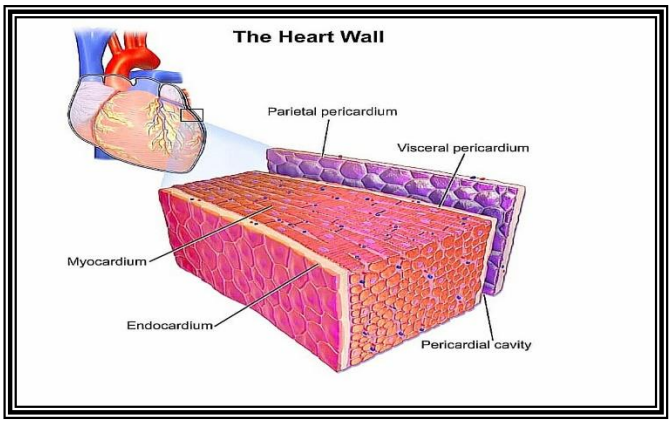

Fig.(1): *3D rendering showing thick myocardium within the heart wall* ***(5)****.*

The basic anatomical features of the heart in the human and the rat are very similar. Thus in both species the heart has four chambers; two atria, separated by an interatrial septum (IAS), and two ventricles, separated by an interventricular septum (IVS). The myocardium is present in the walls of all four chambers of the heart. The two atria are thin-walled chambers that receive blood from the veins, while the two ventricles are thick-walled chambers that forcefully pump blood out of the heart. Differences in thickness of the heart chamber walls are due to variations in the amount of myocardium present **(6).**

Although the structure of myocardium is the same in the atria and the ventricles, the ventricular myocardium is thicker than the myocardium present in the atria. This is due to the greater hydrostatic pressure that the ventricles must overcome when pumping the blood into the systemic vessels **(7).**

The inner wall of the right atrium is formed from two parts; anterior rough and posterior smooth parts separated from each other by a muscular ridge called crista terminalis. Parallel muscular ridges extend from the crista terminalis into the anterior wall of the right atrium giving it a comb-like appearance; these muscular ridges are called pectinate muscles which are responsible for the roughness of the right atrial anterior wall **(Fig.2)**. On the other hand, the inner wall of the left atrium is smooth except for the left auricle which is rough and has many pectinate muscles **(8, 9).**

The ventricular myocardium is made up of three layers; superficial (subepicardial), middle and deep (subendocardial) layers. The superficial and deep layers are present in both ventricles, while the thick middle layer is found only in the left ventricle and constitutes most of the myocardial mass in the left ventricle. This explains why the wall of the left ventricle is three times as thick as that of the right ventricle **(10).**

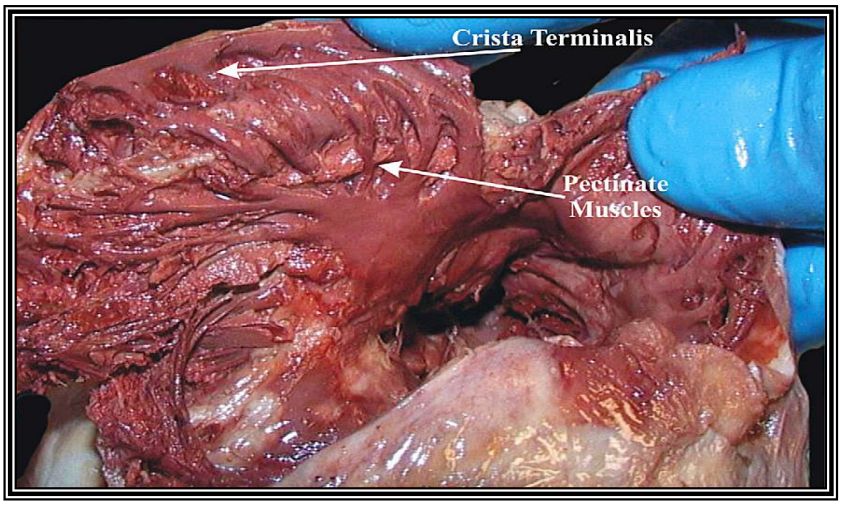

Fig.(2): *Right atrial wall showing crista terminalis and pectinate muscles* ***(9).***

The cavity of the right ventricle is divided into two parts; inflow and outflow tracts separated from each other by the supraventricular crest. The inflow tract is large and rough due to the presence of muscular projections from the ventricular wall called trabeculae carnea, while the outflow tract is smaller, smooth and leads to the pulmonary orifice **(11).**

Trabeculae carnea of the inflow portion of the right ventricle are of several types including ridges, bridges, moderator band and papillary muscles. Ridges constitute just projections from the myocardial wall, while bridges are attached by its both ends to the ventricular wall and free in the middle. Moderator band is attached between the lower part of the interventricular septum and the anterior wall of right ventricle. Papillary muscles are conical muscular projections from the ventricular wall **(12).**

There are three papillary muscles in the right ventricle; Anterior, posterior and septal papillary muscles. The base of each papillary muscle is attached to the myocardium, while the apex gives rise to thread-like glistening bands of fibrous tissue called chordae tendinae which are attached to the cusps of the tricuspid valve **(Fig.3)**. On contracting, the papillary muscles pull on the chordae tendinae to prevent prolapse of the valve leaflets during ventricular systole **(13).**

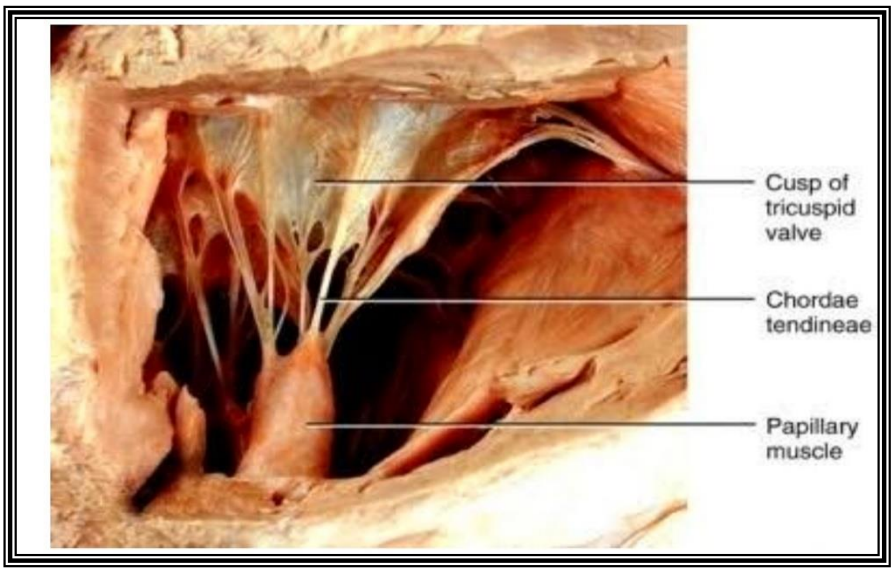

Fig.(3): *Right ventricular wall showing papillary muscle with its chordae tendinae attached to the tricuspid valve* ***(13).***

The cavity of the left ventricle is also formed from two parts; inflow and outflow tracts. The inflow tract is large and its wall is rough due to the presence of irregular muscular projections called trabeculae carnea like those of the right ventricle but they are larger and more complicated than those of the right ventricle. On the other hand, the outflow tract is smaller and its wall is smooth to facilitate the passage of blood into the ascending aorta **(14).**

The left ventricle contains two papillary muscles; anterior and posterior papillary muscles. Their bases are attached to the ventricular wall while their apices give rise to the chordae tendinae which, in turn, are attached to the margins and the ventricular surfaces of both cusps of the mitral valve **(15).**

The rat and human cardiovascular systems have many features in common; however, there are also important differences. Although the rat heart is obviously far smaller than the human heart, the ratio of heart to body weight is similar, as are the relative thicknesses of the right and left ventricular walls. The most prominent anatomical variations between the cardiovascular systems in rat and human are probably those found in the venous components of the atria. All of these variations reflect the species-specific differences in development of the venous tributaries connecting to the inferior atrial wall. Thus, whereas in the human heart the left atrium receives four pulmonary veins, in the rat heart, the pulmonary veins join in a pulmonary confluence behind the left atrium, which in turn empties via a single foramen into the dorsal wall of the left atrium **(Fi4.10) (16).**

Another anatomical difference in the atrial anatomy relates to the venous drainage into the right atrium. During the early stages of cardiac morphogenesis, in both the human and murine embryo, the left and right superior caval veins (LSCV and RSCV) initially drain into the sinus venosus. The sinus venosus itself opens via the sinoatrial foramen into the right atrium. As development progresses, in the human heart the left caval vein regresses and the remaining proximal portion (with part of the left sinus horn) becomes the coronary sinus, the remnant of the LSCV becoming the so-called ligament of Marshall and oblique vein. In the rat, however, the LSCV does not regress and persists into postnatal life **(Fig.4)**. In the human, persistent LSCV is considered a congenital malformation (incidence 1:100) frequently associated with other congenital malformations **(17).**

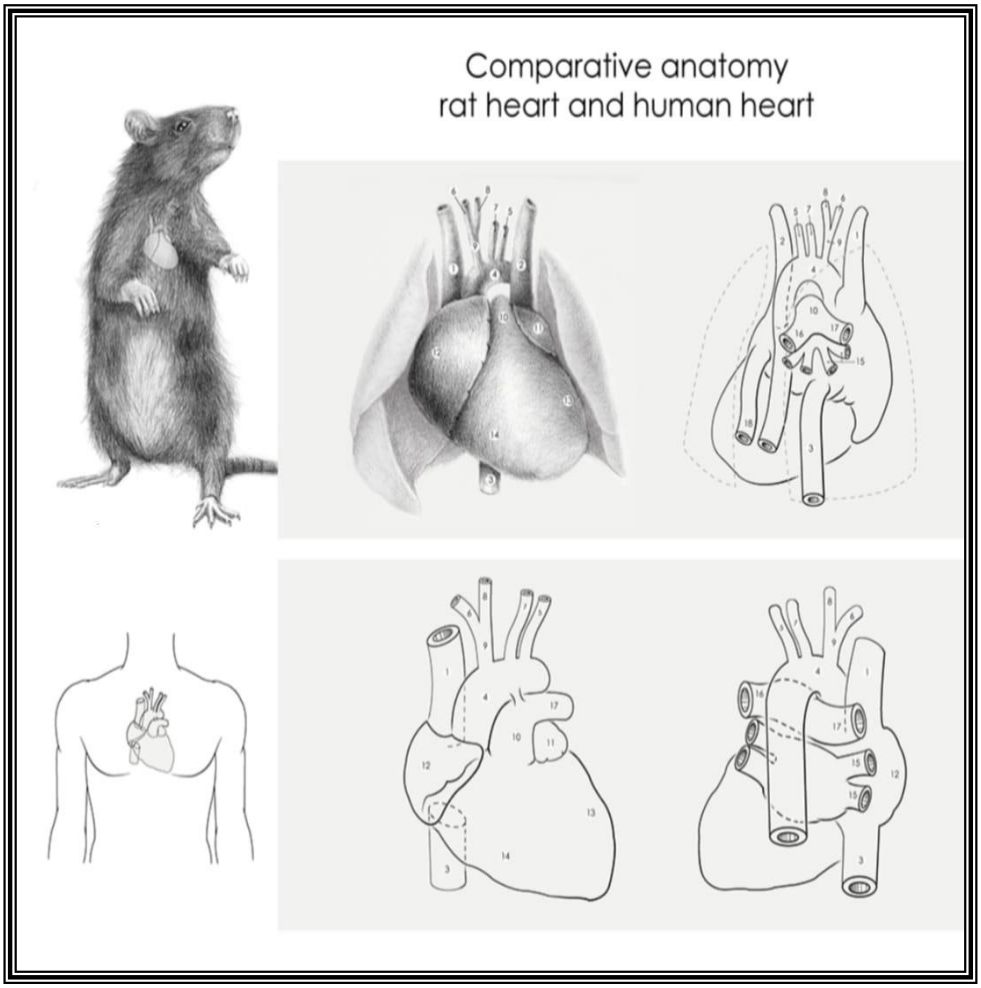

Fig.(4): *comparative anatomy between the rat heart and the human heart. Notice the rat right atrium receive left and right superior caval veins (LSCV and RSCV) while the human right atrium receive only one superior caval vein. The human left atrium receives four openings for the four pulmonary veins while in the rat heart, the pulmonary veins join in a pulmonary confluence behind the left atrium and open via a single foramen into the dorsal wall of the left atrium* ***(16).***

Furthermore, the chordae tendinae in the rat heart are far less prominent than in the human heart and the ventricular trabeculae carnea are absent in the rat ventricles. A slight morphological difference in the overall ventricular anatomy between rat and human is found in the relative size and shape of the muscular ventricular septum. In the human heart the muscular IVS is a massive structure, its thickness approaching or exceeding that of the left ventricular free wall. The human muscular IVS has a very broad base just below the AV valve attachments. In the rat, the IVS is not quite as massive and compact, and at the base it gradually tapers toward the AV septum **(18).**

Cardiomyocytes are the individual cells that make up the cardiac muscle. The primary function of cardiomyocytes is to contract, that in turn generates the pressure needed to pump blood through the circulatory system **(19).**

The myocardium of the heart wall is a working muscle that needs a continuous supply of oxygen and nutrients to function efficiently. For this reason, cardiac muscle has an extensive network of blood vessels to bring oxygen to the contracting cells and to remove waste products. The myocardium is supplied by the right and left coronary arteries which arise from the ascending aorta just above the aortic valve. After blood passes through the capillaries in the myocardium, it enters a system of cardiac (coronary) veins. Most of the cardiac veins drain into the coronary sinus, which opens into the right atrium **(20)**.

The rat has a dual blood supply system in the heart. Several studies have demonstrated that the rat's myocardium is nourished by the coronary arteries and an extracardiac system. The right and left coronary arteries are responsible for supplying the myocardium of the ventricles, the interventricular septum and the atrial septum. Extracardiac vessels are branches from cardio-mediastinal, internal mammary or subclavian arteries. Extracardiac arteries of the right side supply the myocardium of the right and left atria, while the arteries of the left side supply a small portion of the left atrial myocardium **(21).**

The cardiac muscle is innervated by sympathetic and parasympathetic fibers from the autonomic nervous system. The network of the nerves supplying the myocardium is called the cardiac plexus. It receives contributions from the right and left vagus nerves, as well as contributions from the sympathetic trunk. These are responsible for influencing the heart rate, cardiac output and contraction forces of the heart **(22)**.

B- Histology of Cardiac Muscle:

Myocardium shows similar histological features in humans and rats. Atrial and ventricular myocardium have generally similar features, however, atrial walls are thinner and atrial cardiomyocytes tend to be smaller, thinner, and more elongated than their ventricular counterparts **(23).**

Cardiac muscle is composed of individual cardiac muscle cells (Cardiomyocytes) joined by intercalated discs, and encased by collagen fibers and a network extracellular matrix**.** Similar to the analogous structure in skeletal muscle, the endomysium is a collagen network that surrounds individual muscle fibers. The perimysium is a slightly thicker collagen network that surrounds groups of cardiomyocytes. Because these collagen networks are relatively thin and the bundling of cardiomyocytes is often indistinct, they are frequently lumped together as a part of the cardiac interstitium, which includes all components between cardiomyocytes. Within the interstitium, there is a rich vascular network so that each cardiomyocyte is surrounded by multiple capillaries **(24).**

Cell types present in the interstitium include abundant fibroblasts and endothelial cells. In addition, the interstitium contains low numbers of leukocytes (macrophages and lymphocytes) and low (in humans) to extremely low (in rats) numbers of adipocytes. The interstitium also contains a delicate network of extracellular matrix **(18).**

Cardiomyocytes are rectangular, branching and anastomosing cells that may contain one or two centrally located nuclei. Although the majority of rodent cardiomyocytes are binucleated, most human cardiomyocytes are mononucleated. Nuclei have a granular chromatin pattern and one or two prominent nucleoli. Cardiomyocytes contain many mitochondria to produce large amounts of adenosine triphosphate (ATP) and myoglobin to store oxygen to meet the demands of myocardial contraction **(25).**

The individual cardiac muscle cell (cardiomyocyte) is composed of chains of myofibrils, which are rod-like units within the cell. The myofibrils consist of repeating sections of sarcomeres, which are the fundamental contractile units of the muscle cells **(Fig.5) (26)**.

Cardiac muscle shows the organization of thin and thick myofilaments overlapping within the sarcomere of the cell producing the characteristic striated appearance. This striated appearance consists of thick dark-colored A-bands (mainly composed of thick myosin filaments) with a relatively bright H-zone in the center, and lighter colored I-bands (mainly thin actin filaments) with a dark central Z line connecting the actin filaments **(Fig.5) (27)**.

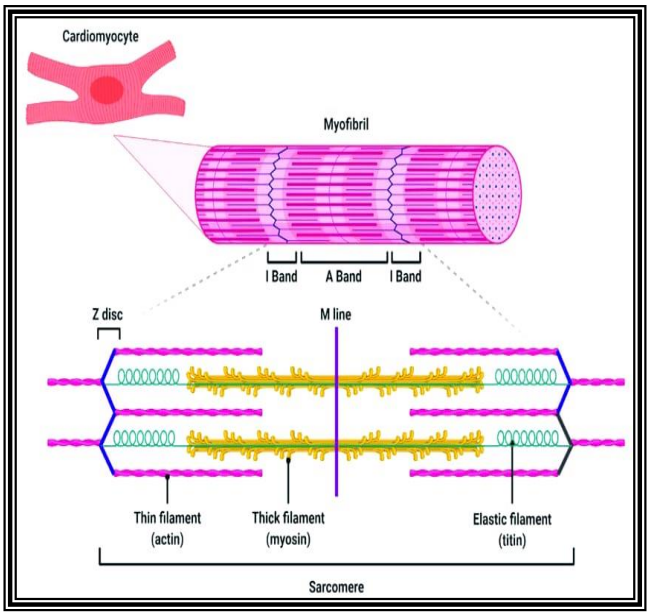

Fig.(5): *Sarcomere structure in cardiomyocytes. Each sarcomere contains rows of interdigitating thin (pink) and thick (yellow) filaments comprised of actin and myosin, respectively. Each titin protein (cyan) spans half-sarcomeres from the Z-disc to the M-line* ***(27)****.*

Neighboring cardiomyocytes are joined together at their longitudinal ends by intercalated disks to create a syncytium of cardiac cells. Within the intercalated disc, there are three different types of cell junctions; fascia adherens, desmosomes, and gap junctions **(28).**

The fascia adherens attach thin actin filaments of the sarcomere to the cell membrane. Desmosomes provide tight mechanical connections between the cardiomyocytes that anchor the ends of cardiomyocytes together and prevent their separation during contraction **(29)**, **(Fig.6)**

Gap junctions are electrical junctions between the adjacent cardiac muscle cells and allow the propagation of action potential from one cardiac muscle cell to the next. Gap junctions ensure the electrical continuity and chemical communication between neighboring cardiac muscle cells **(Fig.6)**. The branched nature of cells and gap junctions allows rapid propagation of action potentials across the entire myocardium; this enables the heart to contract and relax as a single unit (functional syncytium), **(30)**.

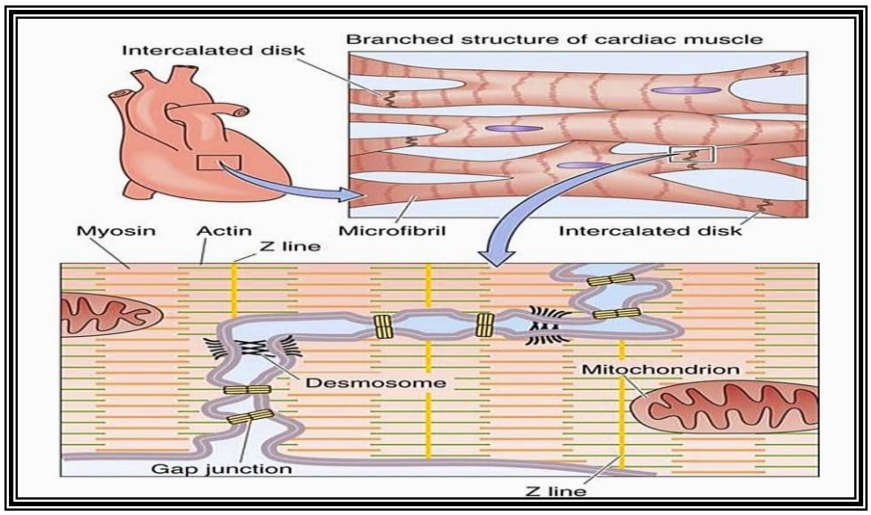

Fig.(6): *Showing cardiomyocytes joined together by intercalated discs, that contain fascia adherens, desmosomes, and gap junctions* ***(31).***

C- Embryology of Cardiac Muscle:

The cardiac muscle develops from myoepicardial mantle, which originates from of the splanchnic mesoderm surrounding the developing endocardial heart tube during the third week of embryonic development **(32)**.

The heart is the first functional organ in the developing vertebrates. It originates from an embryonic tissue called mesoderm around 18 to 19 days after fertilization. The heart begins to develop near the head of the embryo in a region known as the cardiogenic area. The mesenchyme of the cardiogenic area begins to form two strands called the cardiogenic cords. As the cardiogenic cords develop, a lumen rapidly develops within them. At this point, they are referred to as endocardial tubes. Then, the two endocardial tubes migrate together and fuse at the midline forming a single primitive heart tube **(33), (Fig.7).**

The first rhythmic contractions of the heart tube occur at 21-22 days of the embryonic life in humans and at 8.5-9 days in rats. The endocardial heart tube forms the endocardium of the heart, while the surrounding splanchnic mesoderm is thickened forming the myoepicardial mantle, which subsequently forms the myocardium and the Epicardium **(34).**

The mesenchymal cells of the splanchnopleuric mesoderm surrounding the endothelial heart tube elongate and become the myoblasts. Differentiation and growth of each myoblast gives rise to a cardiac muscle fiber. The growth of cardiac muscle fibers occurs due to formation of new myofilaments and myofibrils. The cardiac muscle fibers elongate and give rise to numerous side branches. The side branches as well as the ends of one cardiac muscle fiber adhere to the side branches and the ends of other cardiac muscle fibers, but the intervening cell membranes persist. These sites of adhesion of the cell membranes between cardiac muscle fibers persist as intercalated discs **(35).**

Within the next several weeks, the proliferation of cardiomyocytes is necessary for expanding the myocardial layer. While existing cardiomyocytes contribute to the growth of the myocardium via proliferation and organization, new heart muscle cells are also recruited from adjacent mesenchymal layers that further expand the muscle layer **(36).**

Later in the embryonic period, some myoblasts give rise to few special bundles of cardiac muscle fibers that have few and irregularly distributed myofibrils with relatively larger diameters than the typical cardiac muscles fibers and greatly increased concentration of glycogen in the cytoplasm. These atypical cardiac muscle fibers form bundles called Purkinje fibers, which in turn form the conducting system of the heart **(37)**.

On the other hand, the primitive heart tube quickly forms five distinct regions at 22 days of the embryonic life. From head to tail, these include the truncus arteriosus, bulbus cordis, primitive ventricle, primitive atrium, and the sinus venosus. Then, the five regions of the primitive heart tube develop into recognizable structures in a fully developed heart. The truncus arteriosus will eventually divide and give rise to the ascending aorta and pulmonary trunk. The bulbus cordis develops into the right ventricle. The primitive ventricle forms the left ventricle. The primitive atrium becomes the anterior portions of both the right and left atria, and the two auricles. The sinus venosus develops into the posterior portion of the right atrium, the SA node, and the coronary sinus **(38), (Fig.7).**

As the primitive heart tube elongates, it begins to fold within the pericardium, eventually forming an S shape, which places the chambers and major vessels into an alignment similar to the adult heart. This process occurs between days 23 and 28. After that, the remainder of the heart development pattern will proceed including development of septa, valves and remodeling of the actual chambers. Partitioning of the atria and ventricles by the interatrial septum, interventricular septum, and atrioventricular septum is complete by the end of the fifth embryonic week. The atrioventricular valves are formed between embryonic weeks five and eight, while the semilunar valves are formed between embryonic weeks five and nine **(Fig.7).** These processes result in a mature and fully functional, contracting heart by the eighth embryonic week and throughout adulthood **(39).**

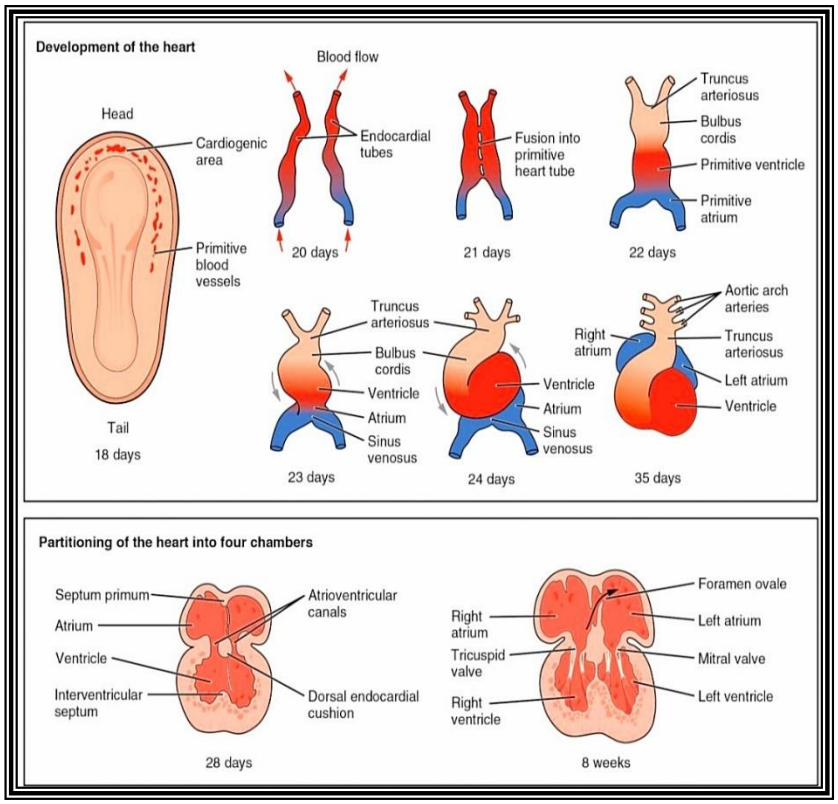

Fig.(7): *Development of the Human Heart: This diagram outlines the embryological development of the human heart during the first eight weeks and the subsequent formation of the four heart chambers* ***(40).***

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