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Anatomy, embryology and histology of aorta

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The aorta is a large elastic artery that originates from the aortic valve and ends by bifurcating into right and left common iliac arteries at the level of the aortic carrefour. This vessel and its branches provide blood supply and oxygen to all the tissues and the organs in human body.

ANATOMY

The aorta is conventionally classified into five sections, according to blood flow: 1) the root or sinus segment, which extends from the aortic valve annulus to the sino-tubular junction; 2) the ascending thoracic aorta, which extends from the sino-tubular junction to the innominate artery; 3) the aortic arch, which extends from the innominate to the left subclavian artery; 4) the descending thoracic aorta, which extends from the left subclavian artery to the diaphragm; and 5) the abdominal aorta, which extends from the diaphragm to the level of the aortic bifurcation. Ascending aorta, aortic arch and descending aorta are represented in Figure 1.1.[1]

In the first two parts, the blood is pumped superiorly, so this component is called "ascending aorta." Ascending aorta has a mean length of 5 cm and mean diameter of 3.5 cm. It is directed upwards, slightly posteriorly and to the right. It is divided in a proximal component called "aortic root" that is connected to the rest of ascending aorta by the sino-tubular junction. The aortic root contains three rounded enlargements called "Valsalva sinuses." Normally, the right coronary artery originates from the right sinus, whereas the left main coronary artery originates from left sinus; the most inferior and posterior sinus does not give rise to coronary artery, therefore it is called non-coronary sinus.

Ascending aorta continues into the "aortic arch," a hairpin turn-shaped portion that travels backward and to the left, loops over pulmonary artery bifurcation and crosses the

left main bronchus. Its mean diameters are 2.9 cm at proximal level and 2.6 cm at distal level. The aortic arch gives rise to three important branches: the brachiocephalic trunk, the left common carotid artery and left subclavian artery from proximal to distal.

Aortic arch continues downwards to the "descending aorta" after a small narrowing called "aortic isthmus." The descending aorta is divided into "descending thoracic aorta" and "abdominal aorta;" thoracic aorta has a mean diameter of 2.5 cm. Its proximal part is located on the left side of the vertebral column, then it is directed to the median line and lies in front of the spine; after passing the aortic hiatus of the diaphragm it continues into the abdominal aorta. Thoracic aorta provides blood supply to thoracic organs including bronchi, esophagus, and rib cage. The abdominal aorta is the distal component of the aorta and has a mean diameter of 1.9 cm; it supplies splanchnic organs by some important branches such as celiac trunk, superior and inferior mesenteric arteries, and renal arteries. The terminal part of the abdominal aorta is represented by its bifurcation into the right and left common iliac arteries.

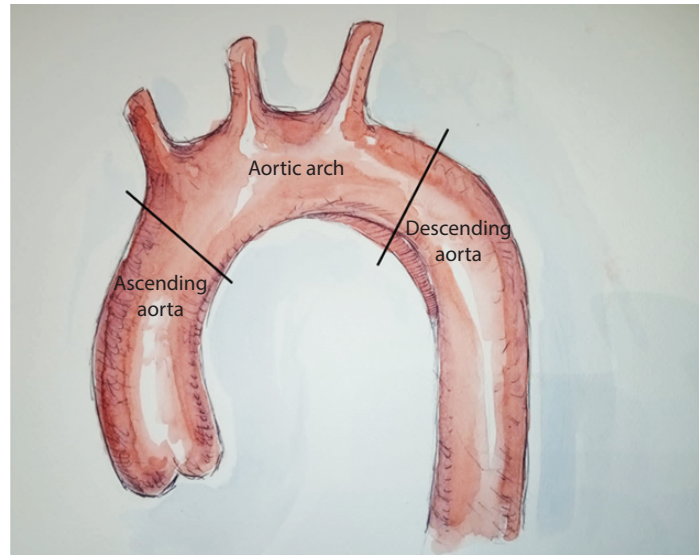

Figure 1.1. First three parts of aorta: ascending aorta, aortic arch and descending aorta.

In addition to the conventional aortic anatomy, there is a more technical classification of aortic anatomy that is used to plan, guide, and report aortic interventions, especially endovascular stent-grafting. Because the clinical success of thoracic aortic endovascular procedures is influenced by the proximal sealing zone, in this system the thoracic and abdominal aorta are divided into 11 landing zones (Figure 1.2):[2]

- zone 0 includes the ascending to distal end of the origin of the innominate artery – zone 0 can be further divided into 0A which extends from the annulus to the distal margin of the highest coronary, 0B which extends above the coronary to the distal margin of the right pulmonary artery, and 0C from the right pulmonary artery to the distal end of the origin of the innominate artery;

- zone 1 involves the portion between the innominate and the left carotid (including the origin of the left common carotid artery);
- zone 2 involves the portion between the left carotid and the left subclavian (including the origin of the left subclavian artery);
- zone 3 involves the area from proximal descending thoracic aorta down to the fourth thoracic vertebral body with the first 2 cm distal to the left subclavian artery;
- zone 4 involves the area from the end of zone 3 to the mid-descending aorta (sixth thoracic vertebral body);
- zone 5 includes the area from the mid-descending aorta to the celiac trunk;
- zone 6 involves the portion between the celiac trunk and the superior mesenteric artery (including the origin of the celiac);
- zone 7 involves the portion between the origin of the superior mesenteric artery and the renal arteries;
- zone 8 involves the portion between the renal arteries and the infrarenal abdominal aorta (including the origin of the renal arteries);
- zone 9 starts from the infrarenal abdominal aorta and ends at the level of aortic bifurcation;
- zone 10 is represented by the common iliac arteries;
- zone 11 involves the origin of the external iliac arteries.

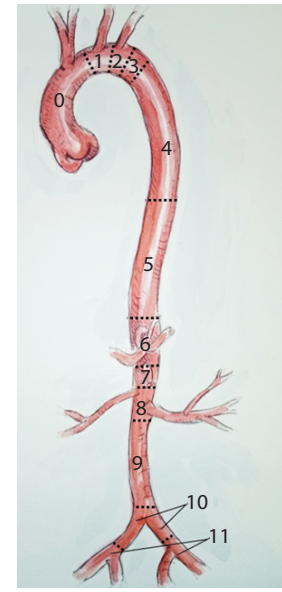

Figure 1.2. Ishimaru's Classification of aortic anatomic segments by 11 landing zones.

EMBRYOLOGY

The three main components of the aorta (ascending aorta, aortic arch, and descending aorta) derive from different cell type. The primitive heart develops from five dilations: truncus arteriosus, conus cordis, primitive ventricle, primitive atria, and sinus venosus.

Ascending aorta and aortic arch derive from neural crest, whereas descending and abdominal aorta derive from paraxial mesoderm[3] (Figure 1.3). These distinct developmental lineages lead to a different type of smooth muscle cells and their expression of matrix metalloproteinase (MMP) and tissue inhibitor metalloproteinase (TIMP); when an imbalance between MMP and TIMP exists, the aortic elastic fibers disrupt, and the aortic wall tends to dilate. Furthermore, the amount of elastic fibers tends to decrease from the ascending aorta to the abdominal aorta, whereas collagen presents an opposite behavior.[4] Therefore, the passage

between the aortic arch and the descending thoracic aorta could represents a *locus minoris resistentiae* and explain the reason why most of the intimal tears are located in this point during aortic dissection.

The ascending aorta and the pulmonary trunk develop from the truncus arteriosus from the fifth week of embryological development. The truncus arteriosus arises as a single outflow tract from the right and left ventricles; because of the invasion by neural crest cells, the aorticopulmonary septum finally divides the truncus into separate vascular channels (ascending aorta and pulmonary trunk).

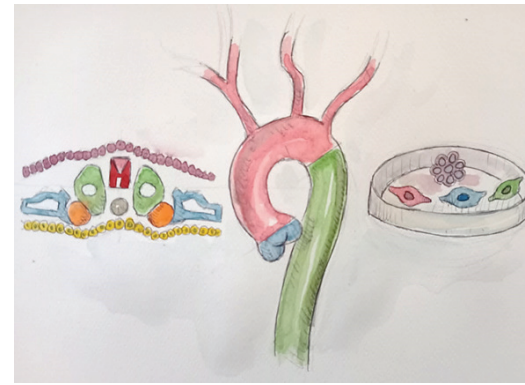

Figure 1.3. Embryological origin of the aorta. Aortic smooth muscle cells originate from three distinct developmental lineages. The aortic root is derived from lateral plate mesoderm (blue), the ascending aorta and arch are neural crest derived (red) and the descending aorta originates from paraxial/somitic mesoderm (green).

The aortic arch has a complex development from different structures. The portion of the arch proximal to the brachiocephalic trunk arises directly from the aortic sac. The medial portion of the arch which includes the innominate artery and the left common carotid artery, arises from the left fourth aortic arch. The portion of the arch distal to the left common carotid artery arises from the dorsal aorta.

The descending aorta develops from the dorsal aorta. This structure derives from the fusion of two dorsal aortas (right and left) at the level of T4 to L4. The dorsal aorta will form the descending thoracic and abdominal aorta.

The aortic sac is a dilated structure superior to the truncus arteriosus. Then, it develops two horn-shaped expansions: the right one forms the brachiocephalic artery, while the left one forms the portion of the aortic arch proximal to the brachiocephalic trunk in combination with the stem of the aortic sac.

The aortic arches develop from the aortic sac and proceed to course into the pharyngeal arches, with a pair of branches (right and left) traveling within each pharyngeal arch and ending in the dorsal aorta. Initially, the arches arise in symmetrical pairs, but after remodeling, the arches become asymmetrical, and several arches regress. All six pairs are not present simultaneously; they develop and regress at different stages. First and second aortic arches regress early, and their remnants give rise to the maxillary, hyoid and stapedial arteries. The third aortic arch contributes to the formation of both the common carotid arteries bilaterally and the proximal internal carotid arteries. The fourth aortic arch contributes to the formation of proximal subclavian artery and the medial portion of the aortic arch. The

fifth aortic arch regresses whereas the sixth aortic arch forms both pulmonary arteries, contributes to the formation of the pulmonary trunk (ventral portion) and the ductus arteriosus (dorsal portion).[5-9]

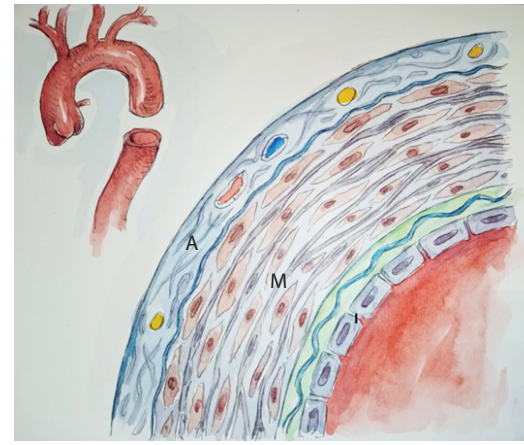

Figure 1.4. A simplified diagram depicting the key histologic components of the aortic wall. From outer to inner layer: tunica adventitia (A), tunica media (M), tunica intima (I).

HISTOLOGY

The aortic wall consists of three layers: the *tunica intima*, the *tunica media* and the *tunica adventitia* (Figure 1.4). The tunica intima is the inner portion of aortic wall, so it is in direct contact with bloodstream. It is thin and composed of a monolayer of endothelial cells and their underlying supporting tissue. The tunica media is the middle portion and the largest portion of the wall; it is composed of elastic fibers, smooth muscle cells and collagenous tissue and polysaccharides sandwiched in >50 layers known as elastic lamellae. Finally, the tunica adventitia is the outermost component of the arterial wall and it mostly contains connective tissue and a few small blood vessels called vasa vasorum that support the cells of the arterial wall.

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Epidemiology and clinical presentations

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Aortic aneurysms (AA) consist of an increasing dilatation of the aortic vascular lumen typically located in the infrarenal abdominal aorta and ascending aorta.[1] Both thoracic and abdominal aortic aneurysms, as well as the aortic dissection, are potentially life-threatening conditions at high risk of rupture. It has been estimated that aortic diseases are responsible for the death of over 10.000 people each year in the United States,[2] and specifically, the AA rupture causes about 175,000 deaths worldwide.[3]

ABDOMINAL AORTIC ANEURYSMS

Abdominal aortic aneurysms (AAAs), characterized by a dilatation greater than 3 cm of diameter or >1.5 times the original size,[4] are more common than thoracic aneurysms. They occur in 4-7% of men, in 1-2% of women and in 80 % of cases they are located between the renal arteries and the aortic bifurcation.[5] Interestingly, their incidence positively correlates with age:[6] it has been reported that the risk of developing an AAA increases by 40% every 5 years after the age of 65[7] and it is six times higher in men than in women[8] although sex differences have not been completely explained by scientific literature. The peak in AAA incidence is around 80 years of age.[7] Moreover, the aortic diameter positively correlates with smoking and the incidence of AAAs is 8 times greater than in non-smokers.[3] Indeed, there is a positive correlation between AAAs and the number of years of smoking.[9] The incidence of AAAs is also associated with the Caucasian race since it has been observed that they are more common in white people than in black populations.[5] The mortality of AAAs rapidly increased during the 20th century, and it is positively correlated with smoking that favors the growth of small AAAs and augments the risk of rupture. However, recent studies suggested that AAA mortality is declining: a retrospective study, conducted in England, Wales and Scotland showed a lower mortality from 1997

to 2009 with a marked sex difference, since the decline was more evident in men than in women. In addition, the reduced AAA mortality was higher in people younger than 75 years old[10] although a mild reduction of mortality existed also in subjects over 75 years of age because of an increased number of elective aneurysm repairs.[10] Overall, these results suggested that clinical relevant AAAs occur at a more advanced age than we previously thought.[10] Another multicenter retrospective cohort study, that included 3248 patients from Northern California with a large unrepaired AAA demonstrated that, the rate of rupture in the early years of the 21th century (2003-2017) was lower than ever and mainly occurred in men.[11] In a similar way, in Australia, the hospitalization rate and mortality for AAAs had significantly decreased since 1999 for both men and women.[12] In addition, using the World Health Organization database, it has been demonstrated that the mortality for AAAs has declined even faster if only the second decade of the current century is considered. The reduced mortality for AAAs could be attributed to several factors, including better blood pressure control and a decreased smoking habit.[13] Moreover, AAA screening should be enforced since it has proven to be effective in reducing mortality as well as AAA-related costs.[12, 13]

Regarding their clinical presentation, it has to be considered that patients with an AAA are usually asymptomatic in 65-75% of cases.[14] Indeed, most AAA are diagnosed incidentally, during radiological imaging for other diseases.[5] Physical examination may reveal a pulsatile abdominal mass. Peripheral arteries must be palpated as one third of large AAAs are associated with aneurysms in the femoral or popliteal arteries.[14] Imaging studies are usually able to reveal incidental AAA: a large study demonstrated that incidental AAAs were found in 1% of abdominal ultrasound, computed tomography (CT) and magnetic resonance imaging (MRI) scans.[15] A small part of AAAs could be symptomatic even if unruptured patients may refer a pulsating abdominal mass and vague lower back pain.[16] This pain, may worsen over time especially if the aneurysm is expanding and is presumably caused by the distention of the peritoneum.[17] Other AAA related symptoms are caused by the compression of surrounding structures: if the bowel is compressed, patients may suffer of nausea, vomiting and sensation of early satiety. In rare cases, and specially in inflammatory aortic aneurysms, duodenal compression can lead to more dramatic conditions, such aorto-enteric fistula, causing severe gastrointestinal bleeding. While the ischemia of the lower limbs is produced by a thrombotic condition within the aneurysm or embolization, AAA could also compress the ileocaval district, leading to peripheral venous hypertension and thrombosis.[14] Unfortunately, in 50% of cases, the first presentation is rupture and it should be suspected in 50-year-old men with abdominal pain.[18] The typical presentation of a ruptured AAA consists of a triad of symptoms: hypotension, back pain that could be extended laterally, and pulsatile abdominal mass, although these 3 symptoms may not occur simultaneously.[19] The pain is often escalating and does not change with position. If the bleeding occurs in the retroperitoneal