Overview of developmental anomaly of the aorta

Poster No.: C-1263
Congress: ECR 2012
Type: Educational Exhibit
Keywords: Congenital, Contrast agent-intravenous, CT, Vascular
DOI: 10.1594/ecr2012/C-1263

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Learning objectives

To review the normal development of the aorta and its various anomalies.

In this exhibition, we will review the normal embryologic development of the aortic arch and suggested hypothesis for its anomaly, specifically the double aortic arch hypothesis of Edwards. And we will also present various types and courses of the aortic arch anomalies, along with the imaging features. Finally, we will describe the symptomatic aortic anomalies.

Through this article, all authors hope that the cardiovascular or chest radiologists will be able to understand the normal embryologic development of the aortic arch and be familiar with their imaging findings.

Background

1. Normal embryologic development of the aortic arch

From the embryologic point of the aortic arch, the most widely recognized is Rathke’s diagram. According to his theory, during the embryologic development, six pairs of the branchial arches connect the two primitive ventral and dorsal aortas. We can number the branchial arches 1 to 6 from cephalad to caudad in regular sequence. The first, second, and fifth arches regress (Fig. 1A). The third aortic arch and a portion of the ventral and dorsal aortic arches form the common carotid arteries (CCAs), external carotid arteries (ECAs) and internal carotid arteries (ICAs), respectively. The fourth arch forms the aortic arch and the ventral bud of sixth arches become the pulmonary arteries. The dorsal portion of the right sixth arch disappears and the dorsal portion of the left sixth arch forms the ductus arteriosus. Finally, the intersegmental arteries migrate cephalically to form the subclavian arteries (Fig. 1B).

2. The double aortic arch hypothesis of Edwards

To understand the aortic arch anomalies, the double aortic arch hypothesis of Edwards is very useful. According to his theory, there are the double aortic arch with the ductus arteriosus on each side, encircling the trachea and esophagus. Each CCA and subclavian artery arises from the aortic arch of same side. And the descending aorta is in the midline. Each specific aortic arch anomalies can be explained by interruption of the double aortic
arch at different locations. The normal aortic arch is formed by interruption of the dorsal segment of the right aortic arch distal from the right subclavian artery (RSA) to the midline descending aorta and the regression of the right ductus arteriosus (RDA) (Fig. 2).

**Images for this section:**

![Fig. 1: Rathke diagram. A. Black-shaded branchial arch segments (numbers 1, 2, 5): portions of arches that disappear. Red branchial arches (numbers 3, 4, 6) remain and develop into arteries. Intersegmental artery(*) B. Long thin arrows indicate cranial migration of intersegmental arteries, which later form subclavian arteries. IA: intersegmental artery, LCCA: left common carotid artery, LECA: left external carotid artery, LICA: left internal carotid artery, RCCA: right common carotid artery, RECA: right external carotid artery, RICA: right internal carotid artery.](image-url)
**Fig. 2:** Schematic representation of the Edward Hypothetical Double Arch. LCCA: left common carotid artery, LDA: left ductus arteriosus, LECA: left external carotid artery, LICA: left internal carotid artery, LPA: left pulmonary artery, LSA: left subclavian artery, RCCA: right common carotid artery, RDA: right ductus arteriosus, RECA: right external carotid artery, RICA: right internal carotid artery, RPA: right pulmonary artery, RSA: right subclavian artery.
Imaging findings OR Procedure details

There are various aortic anomalies grossly categorized by the left aortic arch, right aortic arch and double aortic arch based on the position of the arch. And also, based on the course, interruption and the order or pattern of the branches of the aortic arch, variable aortic anomalies are categorized. Among them, there are ones can cause symptoms.

1. Left aortic arch

A. Left aortic arch with aberrant right subclavian artery

As mentioned above, the normal left aortic arch develops when the dorsal segment of the right aortic arch distal to the RSA regresses. The aberrant right subclavian artery (ARSA) is the most common aortic arch anomaly with a prevalence of 0.5-2% of the population. This anomaly is formed by the interruption of the dorsal segment of the right aortic arch between the right common carotid artery (RCCA) and RSA with the regression of the RDA. So the ARSA is the last branch of the arch, which traverses behind the esophagus and trachea (Fig. 3-4). Often the ARSA arises from Kommerell's diverticulum, which is the remnant of the posterior portion of the primitive dorsal left arch.

This anomaly is usually asymptomatic because the ductus arteriosus is usually left-sided, so vascular ring formation is rare. But, about 10% of patients with ARSA present dysphagia due to extrinsic compression of the esophagus by its retroesophageal course.

Generally, the ARSA is isolated, but maybe associated with the congenital anomalies such as coarctation of the aorta, intracardiac defects or anomalous pulmonary artery circulation.

B. Left aortic arch with the right descending aorta

The left aortic arch with the right descending aorta is rare anomaly, which occurs when a terminal portion of the left aortic arch crosses the midline, as the retroesophageal course, to the right just anterior to the spine and descends along the right side of thoracic spine (Fig. 5). This anomaly can be seen in various forms, depending on the sequence of origin of the aortic branches. The right subclavian artery (RSA) may arise normally from the innominate artery or anomalously from a diverticulum-like structure of the right descending aorta.
Chest radiograph shows the absent left descending aorta just distal to the left aortic arch and the lateral displacement of right posterior medial pleural reflection by the right descending aorta. Barium esophagogram shows the anterior angulation of the esophagus and marked indentation along its posterior wall on lateral view. CT and arteriography more accurately define the right descending aorta (Fig. 6-7).

When the RSA arises anomalously from the right descending aorta, combined with the RDA, complete vascular ring always results. This vascular ring may compress the esophagus and occasionally cause symptoms such as dysphagia. And 75% of patients with the right descending aorta have the congenital heart disease such as Tetralogy of Fallot (TOF).

2. Right aortic arch

The right aortic arch has a prevalence with 0.05% of the population. This anomaly results from the regression of a left dorsal aortic root. The classification of the right aortic arch has been proposed according to the branching pattern of the arch vessels as follows: right aortic arch with mirror-image, right aortic arch with an aberrant left subclavian artery (ALSA), right aortic arch with isolation of the left subclavian artery (LSA) and right aortic arch with an aberrant left innominate artery. And there is another type such as circumflex retroesophageal right aortic arch with an ALSA.

A. Right aortic arch with mirror-image

Right aortic arch with mirror-image results from interruption of a left dorsal fourth arch between the left ductus arteriosus (LDA) and the descending aorta with regression of the RDA. So, as a mirror of normal left aortic arch, the first branch of aortic arch is the left brachiocephalic artery, which is followed by the RCCA and RSA. Usually, the LDA is remaining, but does not form a vascular ring (Fig. 8). About 90% of patients with this anomaly have congenital heart disease such as TOF or truncus arteriosus.

B. Right aortic arch with an aberrant left subclavian artery

Right aortic arch with an aberrant left subclavian artery (ALSA) is the most common type of the right aortic arch, which results from the interruption of a dorsal segment of the left aortic arch between the left common carotid artery (LCCA) and the LSA with regression of the RDA. From proximal to distal, the first branch of aortic arch is the LCCA, followed
by the RCCA, RSA. And the ALSA arises as the last branch of right aortic arch from the Kommerell's diverticulum, which is a remnant of the dorsal left aortic arch (Fig. 9-10).

The patients with this anomaly usually do not present symptoms. But rarely, with the Kommerell's diverticulum and the ligamentum arteriosum, vascular ring is formed, so the patients with vascular ring present symptoms due to airway compression and esophageal indentation. This anomaly is less commonly associated with congenital heart disease.

C. Right aortic arch with isolation of the left subclavian artery

This anomaly has a rare prevalence with 0.8% of patients with right aortic arch. Isolation of the left subclavian artery (LSA) results from the interruption of a left aortic arch at the two positions. One point of the interruption is between the LCCA and LSA and the another point of the interruption is distal to the attachment site of the LDA. So the isolated LSA is connected with pulmonary artery by the LDA (Fig. 11). But, when the LDA is closed, isolated LSA is connected with the left vertebral artery and other collaterals such as external carotid arteries. So, this anomaly may cause subclavian steal syndrome, manifested left upper arm ischemia. A half of patients have congenital heart disease, especially TOF.

D. Right aortic arch with an aberrant left innominate artery

The right aortic arch with an aberrant left innominate artery is rare and only a few cases have been reported in the literature. This anomaly results from the interruption of an embryonic left aortic arch between the ascending aorta and the LCCA with regression of the RDA. So, the RAA give rise to the RCCA and RSA, but the LCCA and LSA arise from Kommerell's diverticulum with a single vessel as the innominate artery that passes as retroesophageal course. With the pulmonary artery anteriorly, aortic arch on the right, Kommerell's diverticulum posteriorly, and the ligamentum arteriosum or ductus arteriosus on the left, a complete vascular ring is formed (Fig. 12). This anomaly has been reported both in isolation and in conjunction with other congenital cardiac anomalies.

E. Circumflex retroesophageal right aortic arch with an aberrant left subclavian artery

The circumflex retroesophageal right aortic arch is uncommon variant of the right aortic arch and the synonym is right aortic arch with a left descending aorta. In this anomaly, the ascending aorta is located on the right side and the right aortic arch crosses midline behind the esophagus at the level of 4th-5th thoracic vertebrae. So the descending aorta
is located on the left side of thoracic vertebrae. The first branch is the LCCA, which is followed by the RCCA and RSA in order. And the LSA arises, as the last branch, from Kommerell's diverticulum (Fig. 13).

This unusual anomaly is often confusing radiographic appearance and resembles a left aortic arch with widening of the mediastinum. So it may simulate the mediastinal tumor or dissecting aneurysm on chest radiograph (Fig. 14).

3. Double aortic arch

This uncommon anomaly results from no interruption in the Edward's hypothetical double arch and persistence of bilateral embryologic fourth aortic arches. As a result, two arches connect the ascending and descending aortic segments. The ascending aorta bifurcates anterior to the trachea, with one arch coursing to the left and the other to the right. The arches rejoin into a single descending aorta posterior to the esophagus, thus forming a vascular ring (Fig. 15). Actually, the double aortic arch is the most common cause of complete vascular ring. The subclavian and carotid arteries arise from their respective arches. So, cross-sectional imaging depicts four great vessels independently from the double aortic arch. About 80% of patients have a larger right aortic arch extends posterior to the trachea and a smaller left aortic arch is usually anterior. This anomaly is rarely associated with congenital heart disease.

Double aortic arches are classified into two types depending upon the patency of the two arches: (A) type1; both arches are persistent and functional, (B) type 2; one of the arches is atretic.

A. Functional(complete) double aortic arches

The two complete arches maybe equal in size or one arch may be hypoplastic. The larger aortic arch is the dominant one, and the right aortic arch is dominant in 73% of patients. This complete double aortic arch is less common than incomplete one. As a clinical aspect, the severity of symptoms is variable depending on the tightness of the vascular ring (Fig. 16).

B. Incomplete double aortic arches (Double aortic arches with atresia of one arch)

When one of the arches is atretic, it is defined as the incomplete double aortic arch. Usually, the left aortic arch may be atretic with fibrous continuity of the affected segments (Fig. 17). Double aortic arch with right arch atresia is theoretically possible, but extremely
rare. The incomplete double aortic arch with a left ductus arteriosus forms a complete vascular ring, which presents symptoms by tracheal and esophageal compression.

4. Other anomalies of aortic arch

A. Cervical aortic arch

When the aortic arch is shifted cranially, extending above the clavicles, it is defined as the cervical aortic arch (Fig. 18-19). This anomaly is very rare with a prevalence of 0.01% of population. There are several proposed theories about the formation of the cervical aortic arch. The first theory proposes the cervical aortic arch is derived from the second or third embryonic arch. The second theory presents lack of caudal migration of normal fourth embryonic arch. The third theory suggests fusion of the third and fourth embryonic arches, combined with failure of caudal migration. The right-sided cervical aortic arch is more common than the left-sided one. There may be many variations such as absent contralateral brachiocephalic artery, anomalus origin of the contralateral subclavian artery, Kommerell's diverticulum and separate origins of the internal and external carotid arteries from the arch.

Clinically, the cervical aortic arch may be presented as a pulsatile mass in the supraclavicular area. And the symptoms depend on the branching pattern of the cervical aortic arch and the presence of vascular ring. Chest radiograph shows ipsilateral superior mediastinal widening and tracheal displacement to the contralateral side. About 20% of patients with cervical aortic arch have an aneurysm.

B. Coarctation of the aorta

Coarctation of the aorta (COA) is defined as a discrete narrowing in the proximal descending thoracic aorta adjacent to the site of the ductus arteriosus and just distal to the LSA. And it is commonly associated with dilatation of the left subclavian artery (Fig. 20).

The exact embryology of the aortic coarctation is not known, but two theories have been proposed. One theory, called ductal hypothesis, suggests ectopic extension of the ductal tissue into the aorta and its circumferential contraction around the aortic lumen lead to discrete aortic narrowing in the juxtaglucal region. Another theory, called hemodynamic hypothesis, postulates abnormally decreased preductal flow. The previous classification into preductal (infantile) and post ductal (adult) is now less commonly used because aortic coarctation is always periductal.
The COA is a common congenital aortic anomaly with a prevalence of 5-8% of patients with congenital cardiovascular disease and has a male predominancy. And it is associated with variable conditions such as the ventricular septal defect, bicuspid aortic valve, patent ductus arteriosus, aortic hypoplasia, Turner's syndrome, or intracranial aneurysms. The clinical features are dominated by systemic arterial hypertension in the upper extremities and systolic murmur.

Chest radiograph shows rib notching as result of the dilated intercostal collateral arteries. And a "figure-3" sign is frequently seen along the left upper mediastinal border, due to the prominent aortic knob above and the poststenotic aortic segment below the coarctation. Cross-sectional images show focal juxtaductal aortic narrowing and multiple collateral arteries such as the internal mammary arteries, intercostal arteries and descending scapular arteries (Fig. 21).

The COA should be distinguished from the pseudocoarctation, which occurs due to the descending portion of the aortic arch at the level of the ligamentum arteriosum is acutely kinked. Clinically, the pseudocoarctation is absent significant hemodynamic obstruction. And radiologically, there are no prominent collateral flows.

5. Symptomatic aortic arch anomalies

Most anomalies of the aortic arch, which described above, are of little or no clinical consequence. But, a minority of these variations may present significant symptoms due to compression of the trachea and esophagus.

The vascular ring is defined as a congenital condition that is the anomalous configuration of the aortic arch associated encirclement of the trachea and esophagus. The structural components for this encirclement are the aortic arches, subclavian artery, circumflex aortic segment, ductus arteriosus or ligamentum arteriosum. Only a small portion of the aortic arch anomalies forms the vascular rings, account for less than 1% of all congenital cardiovascular defects. Some vascular rings are associated with other congenital heart disease and the others may be isolated.

The severity of clinical manifestation depends on the degree of the compression by the trachea and esophagus. In fact, not all vascular rings produce symptoms, also complete vascular ring is not required to produce symptomatic vascular compression of the trachea and esophagus. The majority of patients with a vascular ring present symptoms in infancy or early childhood. Common clinical symptoms related to the tracheal compression are stridor, cyanosis, respiratory distress, exertional dyspnea, wheezing, apnea and chronic cough. In severe obstruction, intercostal retractions during respiration are seen in some infants. Clinical symptoms related to the esophageal compression include dysphagia, recurrent vomiting, difficulty feeding, and failure to thrive. These patients with the vascular rings may be misdiagnosed with airway disease such as asthma.
Of all vascular rings, the double aortic arch and right aortic arch with left ligamentum arteriosum are two most common types with a prevalence of 90% of the cases. Clinically, the double aortic arch, which produces most severe symptoms, is most common and important (Fig. 15-17). And the second most common symptomatic vascular ring is the right aortic arch and left ligamentum arteriosum with ALSA (Fig. 9-10). And there are many other vascular rings that produce symptoms such as right aortic arch with variations, left aortic arch with variations and cervical aortic arches.

Once symptomatic tracheoesophageal compression by vascular rings is confirmed, surgical intervention without delay is definite treatment. Conversely, asymptomatic patients with vascular rings may not require surgical intervention.

**Images for this section:**

**Fig. 3:** Schematic representation of the left aortic arch with ARSA. A. Black-shaded area: the location of the interruption in a hypothetical arch. B. Schematic representation of the evolution of the left arch and ARSA. LCCA: left common carotid artery, LDA: left ductus arteriosus, LPA: left pulmonary artery, LSA: left subclavian artery, RCCA: right common carotid artery, RDA: right ductus arteriosus, RPA: right pulmonary artery, RSA: right subclavian artery.
**Fig. 4:** 60-year-old patient with the periappendiceal abscess. Contrast-enhanced chest CT was taken due to progressive right pleural effusion. Incidentally, axial image of the CT(A) shows the left aortic arch with an ARSA (arrow), which traverses retroesophageal course. On 3D image with right oblique lateral view (B), ARSA is well presented. Esophagus (asterix)
Fig. 5: Illustration of the left aortic arch with right descending aorta
Fig. 6: Four year-old girl, the left aortic arch with right descending aorta. Chest radiograph (A): lateral displacement of right posterior medial pleura by right descending aorta. Aortogram (B and C): left aortic arch with right descending aorta and coarctation of aorta.
Fig. 7: One month-old male, the left aortic arch with right descending aorta. Barium esophagogram with anteroposterior and lateral projections shows posterior impression from retroesophageal aortic arch.

Fig. 8: Right aortic arch with mirror image branching A. Black-shaded area: the position of the interruption in a hypothetical arch. B. Schematic representation of the evolution of the right arch and mirror image branching. BA: brachiocephalic artery, LCCA: left common carotid artery, LDA: left ductus arteriosus, LPA: left pulmonary artery, LSA: left subclavian artery, RCCA: right common carotid artery, RDA: right ductus arteriosus, RPA: right pulmonary artery, RSA: right subclavian artery.
**Fig. 9:** Right aortic arch with an ALSA A. Black-shaded area: the position of the interruption in a hypothetical arch. B. Schematic representation of the evolution of the right arch and ALSA. LCCA: left common carotid artery, LDA: left ductus arteriosus, LPA: the left pulmonary artery, RCCA: the right common carotid artery, RPA: the right pulmonary artery, RSA: the right subclavian artery.

**Fig. 10:** Right aortic arch with an aberrant left subclavian artery (ALSA) in 72-year-old woman without dysphagia. Axial (A) and 3D images (B: posterior view, C: superior view) show right aortic arch with an ARSA (arrow) from Kommerell's diverticulum (K) causing esophageal compression (asterix).
Fig. 11: Right aortic arch with isolation of the left subclavian artery (LSA). A. Black-shaded areas: positions of interruption in a hypothetical arch. B. ILSA: isolated left subclavian artery, LCCA: left common carotid artery, LDA: left ductus arteriosus, LPA: left pulmonary artery, RCCA: right common carotid artery, RDA: right ductus arteriosus, RPA: right pulmonary artery.

Fig. 12: Schematic diagram: the formation of right aortic arch with an aberrant left innominate artery. A: Edwards’ hypothetical double aortic arch plan. RDAR, LDAR: right and left dorsal aortic roots, RSA, LSA: right and left subclavian arteries, RCCA, LCCA: right and left common carotid arteries, DA: ductus arteriosus. B: Formation of a right...
aortic arch with an aberrant innominate artery (INNa). The segment of the left aortic arch from its point of origin to the left common carotid artery (LCCA) is interrupted. Descending aorta (D) C : Volume-rendered computed tomography. DK : diverticulum of Kommerell, LCCA : left common carotid artery, LPA : left pulmonary artery, LSCA : left subclavian artery, RCCA : right common carotid artery, RSCA : right subclavian artery.
**Fig. 13:** Schematic diagram: Circumflex retroesophageal variation of right aortic arch. LCCA: left common carotid artery, RCCA: right common carotid artery, RSA: right subclavian artery, LSA: left subclavian artery.

**Fig. 14:** Circumflex retroesophageal right aortic arch with aberrant left subclavian artery (ALSA) mimicking aortic aneurysm or mediastinal mass in 67-year-old man without symptoms. Anteroposterior view of chest radiograph (A) shows right upper mediastinal widening. Initially, the possibility of aortic aneurysm or mediastinal mass was reported. Axial image of enhanced chest CT (B) reveals the circumflex retroesophageal right aortic arch (asterix) mimicking mediastinal mass or aortic aneurysm. ALSA (arrow) arises from Kommerell's diverticulum (K). t: trachea, e: esophagus. 3D image of same CT (C) also shows retroesophageal right aortic arch (asterix) with an ALSA (arrow) arises from Kommerell's diverticulum (K).
Fig. 15: Schematic diagram of embryology of a double aortic arch. The diagram shows a double aortic arch with ductus arteriosus on each side. There are no interruption in the primitive double arch.
**Fig. 16:** A 12-month-old male with stridor. Axial image of enhanced chest CT (A) shows complete functional double aortic arch forming complete vascular ring. Significant narrowing of the trachea is noted. 3D reconstruction image (B) : double aortic arch encircling the trachea, Red - aorta with vascular ring, Pink - trachea

**Fig. 17:** Double aortic arch with atresia of left aortic arch in a 43-year-old male. Serial axial images of enhanced chest CT (A,B) show a dominant right arch and incomplete left arch. Fibrous continuity (arrow) is suspected from tapered contour of left arch, completing vascular ring. 3D image (C) shows incomplete double aortic arch, more definitely.
Fig. 18: Left cervical aortic arch in 52-year-old female. Posteroanterior chest radiograph (A) shows left superior mediastinal widening. Axial images of enhanced chest CT (B) shows the left aortic arch (asterix) is shifted cranially, extending above clavicle (yellow arrow). 3D image (C), on the left posterolateral view, also shows the left aortic arch (asterix) is shifted cranially, extending above clavicle (yellow arrow). Anomalous origin of left subclavian artery (blue arrow) from the descending aorta is also shown.

Fig. 19: Right cervical aortic arch with subaortic coarse of left brachiocephalic vein in 35-year-old female. Posteroanterior chest radiograph (A) shows bulging of the right paratracheal stripe. Axial and sagittal images of enhanced chest CT (B,C) shows the right
aortic arch (red arrow) is shifted cranially, extending above clavicle (yellow arrow). 3D image (D) definitely shows the right aortic arch (red arrow) is shifted cranially, extending above clavicle (yellow arrow). Incidentally, the left brachiocephalic vein traverses through subaortic course (E, blue arrow).

**Fig. 20:** Illustration of coarctation of the aorta. Diagram shows aortic coarctation (arrowhead), which is focal narrowing of the thoracic descending aorta in a juxtaductal location. Aortic coarctation is commonly associated with dilatation of the left subclavian artery (arrows).
Fig. 21: Coarctation of the aorta in a 49-year-old. Sagittal reformation image of enhanced chest CT (A) and three-dimensional reconstruction image (B) show focal narrowing of the distal aortic arch (red arrows) with associated dilatation of the left subclavian artery (blue arrows). And the collateral circulations such as internal mammary arteries (yellow-green arrows) and descending scapular arteries (yellow arrows) are also showed.
Conclusion

Congenital anomalies of the aorta, which take various forms, result from errors in the development of embryonic aortic arch system. Aortic arch anomalies may have clinical implications or not. Also, these may be overlooked, and often can be confused with other mediastinal masses.

To understand anomalies of the aorta, it is essential to have some knowledge of embryology and the Edward's double aortic arch model.

In this exhibit we presented: 1) the normal anatomy and developmental embryology of the aortic arch 2) Edward's double aortic arch model 3) various types and courses of the aortic anomalies including symptomatic and asymptomatic types. Knowledge and familiarity with various aortic arch anomalies may help appropriate interpretation of images and care for patients.

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References


