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Arterial Anomalies Pertaining to the Aortic Arches and the Branches Arising From Them

Charles William McCorkle Poynter
University of Nebraska Medical Center

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ARTERIAL ANOMALIES PERTAINING TO THE AORTIC ARCHES AND THE BRANCHES ARISING FROM THEM

[6 Plates, 49 Figures]

BY C. W. M. POYNTER

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* *Note.*—The section arrangement above is for the benefit of the Study as a whole and is not meant for the body of the text, where the word section refers only to the classification of the arterial variations.

§ I. INTRODUCTION

For a number of years I have been interested in the arterial variations which have been encountered in my dissecting rooms. Notes have been made of these abnormalities and the literature describing similar conditions has been gradually collected. The more recent textbooks in anatomy devote little space to the subject of arterial variations and the classic works which have reviewed the field are no longer readily consulted; then, too, new facts have been added to our knowledge of arterial development since the most recent of the latter were published. In view of these facts it has seemed worth while to assemble the cases I have collected from the various sources and classify them according to our present knowledge of development.

I wish to take this opportunity to express my thanks to Doctor W. F. Whitney, curator of the anatomical museum at Harvard Medical School, for placing the splendid collection of the Warren Museum at my disposal for study. In the later pages I have used the results of my study freely, referring to the various anomalies as from the Warren Museum.

The following does not purport to be the entire list of all cases reported, for it was not possible with the library facilities and time I had at my disposal to consult all the works that might contain a record of such variations, but I believe a sufficient number have been collected on which to base reliable conclusions of the scope and possibly relative frequency of such abnormalities.

The bibliography at the end of this study includes not only the cases referred to in the body of the work but, in addition, many titles which I was unable to consult but which came to me on good authority. I have included the latter believing that a full bibliography on any subject has a distinct value of its own.

In this study I have confined the observations to those anomalies directly related to the aortic arches and the ventral aorta. In many cases the factor which has produced these variations

seems to have influenced the development of the heart; since, however, no constant relationship could be discovered between the heart anomalies and those of the arches, I will reserve the study of the heart for a future paper. All cases which might be considered to be the result of known pathological processes have been excluded.

Arterial variation is but one of many irregularities encountered in the human body and in order to appreciate it fully we must consider the subject of variation as a whole, otherwise we may be inclined to think that arterial variations have a significance and perhaps an importance greater than any other anomalies encountered.

The first interest which variations had for observers, aside from being simple curiosities, was their bearing on the development of the individual and influence on the various medical and surgical procedures; then with the discovered resemblance to lower forms and the growth of embryological knowledge they assumed greater significance as one of the evidences of man's origin from the same stem as the lower animals. Duval (1884) said: "En effet de cas deux ordres de variations les unes sont un sorte de pas fait vers l'avenir, c'est à dire vers les transformations futures; les autres sont un retour vers le passe c'est à dire vers le transformations déjà subir; les premieres sont des anomalies progressives, les seconds des anomalies regressives." Bateson (1894) said: "Variation in fact is evolution. The readiest way then of solving the problems of evolution is to study the facts of variation."

That all variations should be interpreted as atavistic reminiscence is undoubtedly incorrect. A great many more variations are found in man than in the lower animals. This has been considered as an indication that the average type form is a comparatively recent acquisition, hence instability, also instability due to progressive change toward a type not yet established which will more nearly meet the requirements of the organism. Probably the best way to view the question is to consider variation as belonging to classes. Numerous observations establish a type, then by careful study we are able to classify the variations as belong-

ing to lower types or not. If the anomaly is found in some form below man it is retrogressive, if not it is progressive. This is as far as comparative anatomy can carry us, but comparative embryology has thrown more light on the subject. Mehnert (1895) has suggested a new significance for the variations in the embryo. These variations are of themselves of great theoretic interest, they furnish us with a hint of the growth processes and are not apparently confined to the phylogenetic processes. This consideration of embryonal variations would suggest a third class of variations according to Mehnert, "Als Ungluchheiten in der Art der Entwicklung eines Organs innerhalb derselben Species oder mehrfach vertretener Organe innerhalb eines Individuums zusammenfasst."

When we find in man a condition similar to that found in some lower animal we may assume that the same factors were operative during a certain stage of development which are constant for that animal. This only suggests that at times during development man may be subject to unknown forces which are constantly operative in the lower forms. Objection to the assumption that variations dissimilar to conditions found in lower forms are progressive may be made on the ground that we are too near to judge.

Of the remote causes of variation we know nothing yet and if we assume that at a certain time unusual factors operate in a human embryo to produce a variation we are still ignorant as to what the factors are. With increased knowledge of development the number of anomalies which may be considered as indicative of atavism decrease.

Another feature of variation has been suggested by Keith (1895), who says: "An extended observation will probably show that nearly allied races are more emphatically distinguished by the kind and frequency of their anatomical variations than by what would be described as their typical structure." If this were known to be true we could only speculate as to its significance.

§ II. VARIATION OF ARTERIES

Arterial variations early attracted the attention of anatomists and were recorded as deviations from normal; they soon interested surgeons and it is from this standpoint that Quain (1844) presented his great work; even as late as 1878 Hyrtl considered them principally for their surgical significance. Anatomists who studied the lower animals, as Cuvier (1838), recognized the similarity between some of these anomalies and the normal condition in animals and in recording the variations regularly spoke of the animals in which a similar condition obtains. The growth of the conception that a connection existed between the two, I will speak of particularly in the next section.

Baader (1866) classified a large number of the mammalian conditions as analogous to variations in man. He did not make use of the facts then known concerning development and did not speak of a similarity indicating atavism. His idea of the way in which variations occurred was new; it was in effect that the earliest vessels are arranged as a net and that the great trunks develop through the enlargement of some of these channels while others degenerate. In keeping with this theory his conception seems to have been that the number of possible variations was limitless. Aeby (1871) held the same idea and Krause (1868) made use of a hypothetical plexus in some of his explanations. The conception of an arterial net was purely theoretic with its author but it has since furnished the subject for a controversy which need not be reviewed here.

Ruge (1884) showed that variations fall into certain classes, *i. e.*, are not innumerable, and he considered that a part at least of these variations have an atavistic meaning. The work of Hochstetter, Goeppert, Evans, Lewis and others has contributed much to the general subject of arterial variation but the intimate relation of their work to the subject of this study will permit a detailed review of their researches at proper points in the subsequent pages.

§ III. THE AORTIC ARCHES

The earliest observations on the aortic arches were made on birds; Haller (1758) recognized a stage in the chick when there were three vessels and this was antedated by the work of Malpighi who figured three arches. Pander (1817), in Tab. IX, fig. 3, showed three arches in a three-day chick; these figures are possibly copied from Malpighi, he recognized that early there were two dorsal aortae. v. Baer (1827) also saw two dorsal arteries, saying that about the fortieth hour the blood was forced around the gut in two trunks; these proceed on each side under the vertebral column, probably uniting after having been separate for a considerable distance. Serres (1830) saw between the fortieth and fiftieth hours a double aorta throughout its entire length; he affirmed that the single aorta was formed by the gradual fusion of these two trunks. He does not however seem to have had a clear conception of the branchial arteries.

Rusconi (1817) comprehended the formation of the arterial stems from the vessels of the visceral arches and described the metamorphosis from the fish type for salamander. This work was followed by that of Huschke (1817) and v. Baer (1827) for birds, and v. Baer (1828) for mammals.

Rathke is quite generally credited with originating the diagrammatic figures illustrating the fate of the aortic arches, but I believe the first figure of this kind was made by v. Baer (1828) as fig. 3, Plate IV; see fig. 1 of this study. This figure was referred to by him in his discussion of both birds and mammals and in that discussion he clearly indicates that the right arch persists in birds while in mammals the left remains. As noted in fig. 1 this is a left arch. Thomson (1830) copied the figure as a right arch and introduced a second figure of a left arch which he referred to as representing the mammalian condition.

v. Baer (1828) clearly understood the phylogenetic significance of the aortic arches, for he said, page 518: "Die erste Bildung des Arterien Systems wird aber durch die Halskeimen auf eine bei allen Wirbelthieren, bei den Fischen bleibend, bei den höheren Classen vorübergehend." Rathke (1832) made an exhaustive

study of the branchial apparatus of different forms; he concluded, page 127: "Bei allen Wirblethieren ohne Annahme kommen in die frühesten entwickelungszeit Anlagen zu einem Zungenbein und Keimapparate vor."

v. Baer (1837), as the result of more extensive observations, revised his figure calling attention to the mistake he had made in interpretation of the carotids. The new figure was fig. 14, Plate IV, its general scheme is reproduced in fig. 2 of this study. A comparison of figs. 1 and 2 will show that his idea of the truncus arteriosus and carotids was changed, but he still believed that the subclavians arose from the third arch.

Rathke (1843) criticized the last figure of v. Baer, calling particular attention to the error in the origin of the subclavian arteries. In 1857 he issued his second work and figured the changes for the aortic arches in mammals on Plate VI, fig. 10; this I have copied as fig. 3. Aside from the point just referred to in his earlier work our principal interest in this figure is in the more detailed development of the carotids; he supposed that the basal portion of the third arch by elongation became the common carotids, and of the pulmonary arteries, he said, in speaking of the truncus arteriosus: "Es sendet nur einer von truncus (***) einen Zweig aus der sich Gableförmig theilend auf beide Lungen übergeht, und entwickelt sich darauf mit diesem Zweige und jenen erst erwähnten Canal zu der Lungenarterien, indass der andere fünft Gefässbogen vergeht."

From the time of Rathke's renowned precept of five pouches for the system of embryonal visceral arches the question of a greater number of arterial arches was not raised till van Bemmelen (1886) called attention to the presence in the embryos of reptiles and birds of a rudimentary vessel between the systemic and pulmonary arches. This caused Boas (1888) to review the evidence of his earlier work ('81-'2-'6) calling attention to the origin of the pulmonary artery in amphibia and reptilia from the sixth arch. He concluded that the pulmonary artery arose from the corresponding arches in all vertebrates and that a true arch had been overlooked between the fourth and pulmonary arches.

He prepared diagrams illustrating the supposed fate of the arches, see fig. 4, which have since been quite generally employed.

Zimmerman (1889), acting on the suggestion of Boas, exhibited a reconstruction of a 7 mm. human embryo showing a vessel, not previously described, between the fourth and pulmonic arches; it was described as being about as large as the fourth arch and opening into that arch at both ends. Later the same year he found indications of such a vessel in an incomplete series of a sheep embryo and a complete vessel in a rabbit of the eleventh day, in the latter the vessel ran from the truncus arteriosus to the aortic root.

Tandler (1902) made a study of rat and human embryos; in the former he found irregular vascular buds and in the latter, in two embryos, a vessel running from the truncus arteriosus to the aortic arch. He said, page 341:

Da wir aber bei der Ratte so gut wie bei allen andern Säugern einen fünften Arterienbogen postuliren müssen, glaubte ich mich berechtigt diese Verbindung als ein Analogie des fünften Bogens anzusehen, und dieses um so mehr als ja der fünfte Aortenbogen zugleich Ursprung und Verlauf bei den einzelnen Species, ja bei den einzelnen Embryonen, beispielsweise beim Menschen, different zu sein scheint. . . . Die Annahme, dass es sich hier um eine eigenthümliche Form eines fünften Bogens handelt gewennt meiner meinung nach um so mehr an warscheinlichkeit, als ja dieser Bogen nicht nur sehr früh verschwindet, sondern sich auch sehr spät bildet.

Lehmann (1905) in a study of the pig and rabbit found in the former a vessel connecting the fourth and pulmonic arches and joined with the aortic root.

Locy (1906) reviewed the evidence in favor of a fifth arch but stated no positive conclusions although he was inclined to favor the idea of a true arch.

Soulie and Bonne (1908) studied the mole and found a vessel connecting the truncus arteriosus with the pulmonary arch; they were very insistent in the claim of a true fifth arch and called attention to the exact resemblance to the present condition in selachians. They explained the development of the vessel after the pulmonary arch on the ground of the physiological importance of the latter.

Reagan (1912) studied the pig and found numerous anastomoses in the region between the fourth and pulmonic arches. He concluded that "A fifth vessel, very closely approximating a theoretically perfect aortic arch, can be demonstrated for the pig."

Coulter (1909) worked on the cat and found rudimentary vessels below the fourth arch and concluded that a complete fifth arch develops in the cat.

Lewis (1903) was the first to question the fifth arch. He called attention to the irregular condition of the vessels between the fourth and fifth arches and concluded: "The irregular small arteries around the fourth entodermal pouch do not, as Zimmerman believed, form a distinct aortic arch." Later (1905), he made reconstructions of the arches, together with the pouches in the rabbit, and showed not only a great irregularity of the vascular elements but that there was not sufficient evidence of a fifth entodermal pouch to warrant the claims of six arches, and that the question of the homology of the arch from which the pulmonary artery sprung was, in mammals, still an unsettled one.

In the light of recent work on the early vessels of the embryo it is not sufficient simply to find a vessel to prove the existence of a fifth arch. From my study of rabbits and the negative evidence which the collected variations furnish, I am inclined to accept Dr. Lewis's conclusions. The problem has been particularly covered recently by Bremer (1912), who says:

While not wishing to go too deeply into the controversy on the presence or absence of a sixth aortic arch, I may say that it seems to me that the solution should come from further study of the entodermal pouches, of the branches of the nerves and the cartilages of the region. . . . As far as the early development of the vessels is concerned there is nothing certainly to prove the presence of an interpolated arch.

Quite recently new interest has been given the pulmonary arch and arteries. If the pulmonic vessel is a true arch it has undergone great modification and its interpretation is not as simple as had been supposed. Reagan (1912) says that both the pre-pulmonic caecum and the pulmonic vessel "seem to have been greatly modified, if they ever resembled closely the parts anterior which have generally been considered their homologues." Of the pul-

monic arch, Bremer (1912) says: "In the strictest sense the arch extends only from the dorsal aorta to the pulmonary artery; the ventral part of the vessel usually called the arch is really the ventral aorta."

The development of the pulmonary arteries is readily understood by reference to Bremer's work (1902-6) which shows that Rathke's error was due to a failure to study the early development of the vessels, the condition which he figured being a later stage; see figs. 3 and 5. The arteries in the earlier stages develop one on each side and shift to the left with the growth and torsion of the truncus pulmonis about the bulbus aortae.

The subclavian arteries already referred to, fig. 3, Rathke (1857) considered arose as figured and arrived at the adult condition by a shift of the arch and a coalescence of the roots of the subclavian and carotid. This explanation was accepted till 1888 when Mackay presented a study of the subclavians in the chick. This was followed by the work of Hochstetter (1890), Goeppert (1908) and Evans (1909) for mammals, which established the origin of these arteries from a number of segmental arteries, variable in number, from the dorsal aorta. This work agrees with or explains the variations of the subclavians so frequently encountered. Figs. 5 and 8 illustrate the possibilities of origin of these arteries.

We are indebted to Hochstetter (1890) and to its further elaboration by Kemmetmüller (1911) for the correct interpretation of the origin of the vertebral arteries. Fig. 6 illustrates diagrammatically the origin of these arteries and their possible variations.

I have reviewed the embryonal history of these vessels in order to establish a basis for classification and explanation of the variations which are to follow. While we are not directly interested in the earliest stages of the bloodvessels, all of the recent work has shown that many vessels are preceded by plexus formation, though not to the extent suggested by Baader, and this fact may account in a few cases for the formation of unusual anomalies which do not seem to belong to the general classifications.

§ IV. COMPARATIVE ANATOMY.

As already intimated, early observers were impressed with the resemblance of certain variations encountered in man to conditions which were type forms for the lower animals and this led to early group classification of these anomalies according to the arrangement of the trunks which sprung from the aortic arch. While many of the variations may be explained by the figures developed in the preceding section, there are others relating particularly to the arch which cannot be so explained. Among mammals in which the same primary arrangement of arches occurs and in which the same parts of the arches atrophy a difference in types is found. For the sake of brevity we will speak here only of the general principles and leave details of type for the later sections.

Turner (1862) believed that the modification of the early vessels brought about by the movement of the heart into the thorax was responsible for the various forms encountered. While more recent embryological observations have more fully explained the definitive arches and subclavians and have confirmed the migration of the heart, they have failed to detect differences in migration or other factors which would explain the various types extant. Dr. Owen (1868) suggested that the best service of the body economy would determine the type, but in the light of recent biological studies we must look for a more tangible factor. Many exhaustive observations have been carried out in attempts to throw light on the subject but it will not be profitable to consider them here for they simply furnish morphological data.

It seems to me that the point of particular interest to us in this study is the relation of human variation, if any, to type forms in the lower animals and the significance of variation per se. An idea which has been most popular is that the type of chest shape and the degree of descent of the heart are determining factors of the normal. Observation has failed so far to establish a relation between chest shape and the anomalous arrangement of the branches of the arch, possibly because it is of a transient character. As to the significance of an animal type in man we may

quote Keith (1895): "It is doubtful if one can legitimately construe this . . . as an atavistic tendency; more probably it has no more morphological worth than the degree of interdigital webbing."

Parsons (1902) has made an exhaustive comparative study and as a result of this thinks Keith is not warranted in drawing the above conclusion from the data available. He very strongly favors the idea that the comparative breadth or narrowness of the upper opening of the thorax is the chief determining factor in the arrangement of the trunks springing from the aorta. In respect to variations from the normal types among lower animals, all observers are agreed that they are unusual; from this fact he concludes: "These human anomalies are quite new and tentative attempts to meet some changed condition in man as progressive variations which may or may not become more common as time goes on."

For the sake of comparative interest in taking up the various classes of anomalies the animals having a similar condition as normal will be listed.

§ V

I. IRREGULARITIES IN THE DEVELOPMENT OF THE TRUNCUS COMMUNIS ARTERIOSUS

The irregularities in this section will involve structures which belong in development to the heart, but I have chosen to consider them with the arteries because such cases are generally reported with vascular anomalies and because division from a purely developmental standpoint is impracticable. The close association of this, or, more properly, these structures, with the general development of the heart is suggested by the fact that in almost all of these cases of anomalous development there are associated cardiac defects, the most frequent of these is incomplete interven-tricular septum. Later it will be necessary to review briefly the development of these structures when associated heart defects will be referred to in detail.

A. Absence or Imperfect Development of the Aortico-Pulmonary Septum

Irregularities in the development of the proximal portion of the aorta and the pulmonary arteries can only be appreciated by comparison with the various embryonal stages. As briefly reviewed on page 10 the process of development of the aortico-pulmonary septum is seen to be a complicated one and probably it is dependent on many factors. That some of these are coupled with the development of the heart there can be no doubt; this is suggested by the fact that in case of absence of the septum (persistent truncus communis) the ventricular septum is frequently rudimentary and is always defective at the base. The common trunk may open from the right side of the common ventricle as in an early stage of development or when the heart is well developed it may open from both ventricles over the defect in the interventricular septum. When the aortico-pulmonary septum is entirely absent the common trunk gives off the two pulmonary arteries separately from its lateral or dorsal wall and continues as the normal ascending aorta; see fig. 5. The common trunk is generally considered as the homologue of the aorta and the case is referred to as lacking a pulmonary artery, but this is incorrect if we are dealing with a truncus arteriosus in which the septum has failed to develop. It is the structure from which both the aorta and pulmonary arteries are differentiated and consequently represents both in an imperfect state of development. If there is no other defect in the region but the absence of a septum the pulmonary arteries will be given off one on each side of the common trunk. This condition is extremely rare, Keith (1909).

The septum may begin to develop normally, then be arrested; in such cases a truncus communis arises from the heart, then divides into an aorta and pulmonary trunk, Clarke (1885). The septum may be present but defective; in Rokitansky's case (1875) the external appearance was very much like that of the case just cited, but a remnant of septum was present in the common trunk. If the factors producing the anomaly have only a minor influence,

they will be indicated by a communication between normally differentiated arteries, Hektoen (1905).

Not all cases of a single trunk from the heart belong to this class of irregularities. The cases of Farre (1814) and Foster (1846), Vierordt thinks, are cases of atresia of the aorta; atresia of the pulmonary artery will be discussed on page 14. Since these cases seem to represent arrest of development of the aortico-pulmonary septum and are in a measure independent of the accompanying cardiac defects I have classed them together.

The following represent all of the degrees of the anomaly included in section I, A:

Wilson (1798), Standert (1805), Lawrence (1814), Meckel (1816), Tiedemann (1825), Breschet (1826), Martin (1826), Mayer (1827), Blumhardt (1834), Crisp (1847), Dubrueil (1847), Clark & Owen (1848), Toynbee (1849), Hale (1850), Chevers (1851), Deutsch (1851), Hyernaux (1851), Pozzi (Chevers 1851), Vernon (1856), Bernard (1860), Wilks (1860), Turner (1862), Fraentzel (1868), Hickman (1869), Messenger (1873), Rokitansky (1875), Baginsky (1879), Crocker (1879), two cases, Caesar (1880), Peacock & Reed (1880), Rickards (1881), Grant (1883), Berrand, Barry & Rachet (1884), Brewer (1885), Brocq (1885), Clarke (1885), Barbillon (1886), Ziegenspeck (1888), Muhr (1889), Pryor (1889), d'Renzi (1889), Klipstein (1890), Charrin & Le Noir (1891), Girard (1895), Gallois (1896), Cade (1897), Cazin (1897), Petschel (1897), Civatti (1900), Orłowski (1902), Gutkind (1903), Lefas (1904), Rispal & Bay (1904), Keith (1909), Wenner (1909), Dickson & Fraser (1914).

B. Atresia of the Pulmonary Artery Usually Accompanied by Perforate Septum Ventriculare or Patent Ductus Arteriosus

Perhaps no form of cardio-vascular defect is more familiar to the general student than pulmonary stenosis, on account of its comparative frequency and marked clinical manifestations. It has been exhaustively studied by Kussmaul (1865), Rauchfuss (1878) and Vierordt (1898), consequently I will not review the large literature but will confine this classification to the cases in which the pulmonary artery is not functional.

In the cases of atresia of the pulmonary artery, as in other anomalies, different degrees of the defective development are to be found; *i. e.*, all of the variations from a normal artery with ob-

literation of its cardiac opening to a slender fibrous cord in the normal position of the artery. It seems questionable however whether the same factors have always been operative in producing these two extremes; see fig. 35.

The case of Weiss (1875) is interesting as representing atresia in the conus, the pulmonary valves were present and the artery otherwise normal. The most frequent site of obliteration is a narrow band completely constricting the lumen of the vessel in the wall of the ventricle; it may however extend for a variable distance on the arterial trunk. When the artery is represented by a fibrous cord the aorta is usually very large and by its position, opening over both ventricles, suggests an unequal division of the truncus arteriosus by an anomalously placed aortico-pulmonary septum rather than a degenerative process or arrest of development of the pulmonary artery after it has been differentiated. The theory that the condition is due to a foetal endocarditis is generally giving place to the opinion that a developmental disturbance is the causative factor.

This anomaly is in the majority of cases coupled with defective development of the septum ventriculare. Rauchfuss only knew of fourteen cases in which the septum was complete and six of these were his own. It is interesting to speculate on the relation between the two conditions and I am inclined to think from the evidence at hand that the obliteration of the pulmonary artery is the primary condition and that the failure of the ventricular septum to close, like the persistence of the ductus arteriosus, is in the nature of adaptation. The pulmonary circulation is usually carried on through a patent ductus arteriosus but in rare instances this closes normally when the bronchial arteries enlarge and assume the added function, Meckel (1816). This is one of the most remarkable examples of structural adaptation that has been recorded.

Fig. 33 is an example of the usual appearance of the anomaly and the following cases are illustrative of its varying degrees.

Fleischmann (1815), Breschet (1826), Cerutti (1827), Mauran (1827), Lediberder (1836), Laurence (1837), Mansfeld (1843), Chevers (1846), Peacock (1848), Wallis (1850), Bednar (1852), Clar (1857), Marey

(1857), Meyer (1857), Sturock (1859), Hervieux (1861), Rauchfuss (1864), Arnold (1868), Vulpian (1868), Semple (1870), Peacock for Royds (1870b), Peacock (1871), Peacock (1874), Heineman (1878), Crocker (1879), Schrötter & Chiari (1879), Luneau (1880), Stifel (1880), Cronk (1881), Turner (1883), Ashby (1884), Hayward (1884), Leo (1886), McKee (1887), Habershon (1888), Murray (1888), Northrup (1888), Bingham (1889), Wagner (1889), Griffith (1891), Moore (1892), Burgess (1893), Probyn-Williams (1894), Grothe (1898), Löwenthal (1900), Thomson & Drummond (1900), Champeter & Carton (1903), Schreiber (1903), Cohn (1904), McCrae (1906), Keith (1909), Hebb (1913), Milland (1914).

C. Transposition of the Aorta and Pulmonary Artery

Abnormal positions of the great vessels coming from the heart have generally been discussed under the head of "transposition of the aorta and pulmonary artery" and reported cases are generally found in connection with accounts of congenitally defective hearts. Transposition, like the conditions considered in the preceding sections, seems to bear a very close relation to cardiac development and is most frequently found in conjunction with defective septum ventriculare.

It is not necessary to develop the subject in detail, for the work of Rokitansky (1875) still stands, in spite of recent contributions to the history of development, as the most lucid and complete discussion of the subject that has been made. Although the anomaly belongs in part developmentally to the heart, it is included in this study because it is generally reported as an arterial variation. In order to classify the types of the anomaly in harmony with recent discoveries it will be necessary to review the points of development and the theories advanced concerning the etiology of the condition.

The more recent investigations have shown that the bulbus cordis of more primitive forms is represented in the mammalian heart, Greil (1903); early forming part of the anterior limb of the heart; then it is absorbed partly into what becomes later the right ventricle and partly into the truncus arteriosus. The elongated truncus arteriosus becomes differentiated into the aorta and pulmonary artery through the aortico-pulmonary septum, which

appears at the cephalic end of the truncus and grows proximally to unite with the distal and proximal bulbar swellings and finally its interventricular border is attached to the interventricular septum, while dorsally it probably assists in forming the pars membranacea septi. During this complicated process of division of the elongated truncus the aortico-pulmonary septum describes a spiral in a clock-wise direction of about 135 degrees. In lower forms (*Lepidosiren*) this spiral is carried for 270 degrees, Robertson (1913), p. 195. Distally the septum extends laterally, dividing the truncus into a dorsal (pulmonary) and ventral (aorta) compartment, fig. 18 I. Proximally the rotation of the septum through 135 degrees has changed the relations so that the dorsal compartment is the aorta and the ventral compartment is the pulmonary artery, fig. 18 II. Through the rotation of the ventricular cardiac loop which has been going on while this process is being completed in the truncus, by the time the aorta and pulmonary artery have become independent vessels they have established definite relations with the left and right ventricles, fig. 18 III. We may consider this region as made up of four separate elements, viz., truncus arteriosus, bulbus cordis, ventricular limb and arterial limb.

The normal movements of rotation during development may be reversed, that is rotation may be counter clock-wise. When all the viscera share in this condition it is known as situs viscerum transversus. More than three hundred cases have been reported and an analysis of them shows that many are in every respect normal aside from the fact that the viscera and their arrangement is a mirror picture of the normal, Gruber (1865). What factors are operative in the production of situs viscerum transversus is not known. v. Baer described a chick which had rotated in the reverse direction and suggested that this might be the cause of the condition. Thomson (1830) accepted this theory, but it is wanting in proof. I have very carefully reconstructed the viscera of such an embryo which I have in my collection and find that in this specimen all structures are normal in position and development. Another theory which has been advanced by several authors, Virchow (1861), is that situs trans-

versus is the result of mechanical influences acting through the persistence of the right-sided umbilical and omphalomesenteric veins. Dareste (1877) and Fol & Warynski (1881) have produced the condition experimentally, but have added little to our knowledge of its etiology. The orderly reversal of structures in true situs transversus does not always occur, Lochte (1894) having collected thirteen cases in which only part of the viscera had rotated in the wrong direction.

It has long been recognized that the heart may be transposed while the abdominal viscera and the lungs are normal. This condition is known as dextrocardia. A review of the literature shows that observers have no clear idea of this congenital condition, for cases of pathologically displaced hearts are frequently reported under this head and clinical diagnoses are frequently made notwithstanding the fact that the condition is extremely rare.

Both in cases of situs viscerum transversus and dextrocardia alone the heart and great vessels may show anomalies similar to, *i. e.*, mirror pictures of, those encountered in individuals who are normal except for the defect in question. It follows that the anlage of the heart not only does not always follow the other structures either in situs solitus or situs transversus but that one loop may be normal and one or both of the other loops transposed. Lochte (1898) formulated the general conclusion, "Jede korrigierte Transposition bei situs solitus ist einfache Transposition bei situs transversus."

The cases of situs viscerum transversus are too numerous to burden this report with their repetition, but I have included the following cases of dextrocardia for the benefit of those who may be interested in their more careful study.

Eschenbach (1769), Abernethy (1793), Otto (1816) 2 cases, Breschet (1826) 2 cases, Meckel (1826), Otto (1829), Jasinski (1861), Falck (1877), Kriezer (1880), Pope (1882), Kundrat (1888), Grunmach (1890), Graanboom (1891), Lochte (1894), Paltauf (1901), Nagel (1909), Geissler (1911).

As has been shown, we cannot consider the anomalous position of the great vessels independently of the heart, and before we

can attempt to classify them we must understand the theories that have been advanced accounting for their production. Rokitsky (1875) believed that if the concavity of the aortico-pulmonary septum be reversed the relative position of the aorta and pulmonary arteries would be reversed. Since the septum is movable all degrees of such deviation could occur. He described and figured sixteen different forms of transposition which he believed could occur, due to different degrees and combinations of deviation and nonunion of the aortico-pulmonary septum and the septum interventriculare. In the light of recent work, Robertson (1913), there are inconsistencies in his figures which in a measure destroy the classification. Also he considers a ventricle, even when furnished with a bicuspid valve, as right, so long as it occupies a position to the right of the other ventricle. This method of interpreting ventricles leads to some confusion which may be avoided if we identify the ventricles as bicuspid and tricuspid ventricles.

Keith (1909) suggested that the atrophy of the bulbus cordis around the pulmonary artery is responsible for transposition. He, however, was apparently unaware of the function and development of the spiral valve in the dipnoan heart which carries the rotation two hundred and seventy degrees and would therefore reverse the position of the aorta and pulmonary artery and accordingly vitiates his theory and spoils his diagram (Robertson 1913).

Robertson concluded from a study of the lower forms that "If the bulbus cordis develops as a short straight tube without any disparity in the length of the walls of its middle segment, no torsion of the vessels, that is the aortico-pulmonary septum, will take place, the middle part of the bulbus cordis where it should occur being so to speak wiped out." Since the position of the great vessels is determined by the position of the proximal bulbar ridges and these, theoretically, may occupy any position, the aortic and pulmonary orifices may be found with the aorta in front of the pulmonary artery and rotating clock-wise at any point in an arc of 270 degrees, or rotating counter clock-wise at any point in a similar arc the pulmonary orifice may be rotated about the aorta.

Less than normal torsion, that is a rotation of the pulmonary to the left about the aorta through an arc of 90 degrees, may occur with no physiological disturbance, for the ventricular loop adapts itself to the slight abnormality and the structures as a whole develop along normal lines. Such a condition is easily overlooked and is only important as illustrating a stage of more extreme conditions. Robertson (1913*a*) has reported four such cases and I have observed the condition in a foetus with rachischisis.

More than normal torsion, that is the pulmonary artery occupying a position in front and to the right of the aorta, is also likely to be overlooked and will not disturb the general development. The condition is perhaps most interesting as suggesting the reptilian condition. The case of Crocker (1880) is illustrative.

All of this type of anomalies encountered cannot be explained by the torsion of the septum, and to account for these Lochte (1898) has suggested that the ventricular loop may twist normally or the reverse independently of the other parts of the heart. What factors determine the direction which the ventricular limbs will take are unknown, but it seems reasonable to suppose that they might take a reverse direction without affecting the rest of the heart.

Lewis (1915) has accepted this theory and by modeling the heart with the ventricular loop in reverse rotation has shown that such development is possible. Lochte (1898) carries the theory farther and supposes that a left-to-right twist of the left around the left deviation of the interventricular septum, may occur and bring about a transposition of the tricuspid and bicuspid valves.

To make a classification we may consider the truncus arteriosus, aortico-pulmonary septum, and ventricular loop acting independently. The truncus, leaving out intermediate positions, may assume three positions: (*a*) nonrotation (transposition); (*b*) rotation to the right (situs transversus); (*c*) rotation to the left (normal). The ventricular loop may rotate normally or the reverse, situs transversus. This will give six possible positions or combinations, of which one is the normal and another is the mirror of the normal or situs transversus. Of the four remaining combinations two may be discarded, since they are physiolog-

ically normal, Crocker (1879); they are represented in figs. 22 and 23.

The two remaining combinations are generally known as transposition of the aorta and pulmonary artery; they may be described as follows:

1. A failure of rotation of the aortico-pulmonary septum in a heart in which the ventricular loop has rotated normally. The aorta is situated in front of the pulmonary artery and opens from a tricuspid ventricle. This is the most frequent form of transposition, fig. 20.

2. A failure of rotation of the aortico-pulmonary septum in a heart in which the ventricular loop has rotated in the reverse direction. The aorta is situated in front of the pulmonary artery and opens from a tricuspid ventricle. The condition is the mirror picture of "1" and might be found in a case of situs viscerum transversus. For explanation see fig. 21.

3. A group of cases which do not fall in either "1" or "2" have been encountered. The aorta is in front of the pulmonary artery and opens from a bicuspid ventricle. The condition is very unusual and I know of no theory to account for the anomaly which does not present great difficulties. I have offered the theory of Lochte, which Wenner (1909) thinks is satisfactory, as presenting the most logical explanation; see fig. 24.

The following illustrative cases are arranged according to the classification just given for transposition:

Transposition, Class A: Langstaff (1811), Baillie (1812), Farre (1814), Lawrence (1814), Meckel (1816), Otto (1816), Wolf (Ref. Kreysig 1817), Kreysig (1817), Nasse (1821), Müller (1822), d'Alton (1824), Burkart (1825), Tiedemann (1825), Breschet (1826), Bock (Ref. Cerutti 1827), Holst (1836), Martin (1839), Ducrest (1840), Ewen (1840), Friedberg (1844), King (1844), Beck (1846), Parker (1847), Jackson (1849), Parker (1849), Johnson (1851), Ward (1851), Keil (1854), Peacock (1855), Meyer (1857), Reynolds (1857), Hervieux (1861), Cockle (1863), Libert (1863), Meigs (1867), Arnold (1868), Fränkel (1870), Kelly (1871), Pye-Smith (1872), Ogston (1874), Barlow (1876), Maier (1876), Elliot (1877), Jane-way (1877), Martin (1877), Babesiu (1879), Chiari (1879), Mackenzi (1879), Mazzotti (1879), Lees (1880), Ashby (1881), Kleinschmidt (1881), Peacock (1881), Talini (1881), Bianchi (1882), v. Etlinger (1882), Holl (1882), Peacock (1882), Pope (1882), Scott (1882), Crocker (1883),

Gelpke (1883), Marchand (1883), Turner (1883), Combes & Christopher-son (1884), v. Maschka (1884), Shattuck (1884), Toennies (1884), Tooth (1884), Bull (1885), Durozier (1885), Epstein (1886), Bury (1887), Harris (1887), Schrötter (1887), Fussell (1888), Birmingham (1889), Gampert (1889), Miura (1889), de Renzi (1889), Revilliod (1889), Audry & Lecroix (1890), Dorning (1890), Hebb (1890), Hochsinger (1891), Mirinescu (1893), Saunders (1893), Lochte (1894), Bonne (1895), Thérémén (1895), Litten (1896), Monod (1896), Rheiner (1896), Valenti & Pisenti (1896), Reifschläger (1897), Rolleston (1897), Freyberger (1898), Ramm (1899), Rolly (1899), Meinertz (1901), Peters (1901), Champeter & Carton (1903), Cowan & Ferguson (1903), Brain (1905), Chartier (1905), Ellis (1905), McCrae (1905), Apert & Brézaud (1906), Emanuel (1906), Young (1907), Keith (1909), Marchand (1909), Wenner (1909), Robertson (1911), Variot & Moranci (1911), Sato (1914).

Class B: Gamage (1818), Hickman (1869), Schrötter (1870), Graanboom (1891), Griffith (1891), Birmingham (1892), Stokes (1909), Wenner (1909).

Class C: Walshe (1842), Stoltz (1851), Gutwasser (1870), Pye-Smith (1872), Rokitansky (1875), Rauchfuss (1878), Toennies (1884), Mann (1889), Grunmach (1890), Lochte (1898), Thiele (1902), Wenner (1909).

§ VI

II. IRREGULARITIES IN THE DEVELOPMENT OF THE AORTIC AND PULMONIC ARCHES AND THE ROOTS CONNECTING THEM

I have already outlined in a preceding section the growth of our knowledge concerning the development of the aortic arches. From this we see how slowly a clear understanding of the intricate steps of development has been reached, and it is not therefore surprising that the anomalies encountered in this region were not sooner explained and classified. One of the most important steps in clearing up these cases was the paper by Wood (1859) showing the developmental process in the production of the abnormality of a right subclavian artery as the last branch of the arch, see fig. 12.

Turner (1862) collected many cases of irregularity and classified them according to the developmental error. Thomson (1863) criticized Turner for not sufficiently emphasizing by classification the difference between simple cases of right aortic arch

and those associated with inversion of the heart. He offered a substitute classification which is in many respects less satisfactory than the one criticized. Krause (1868) added many cases to those reported by Turner and presented a somewhat different arrangement of them.

A review of all that has been offered in the literature concerning the proper arrangement of the abnormalities under consideration tends to impress one with the fact that no single classification will meet all requirements. I do not offer this arrangement as an improvement on what has gone before, but as the simplest method of presenting the material collected. A few cases in which there is marked disagreement from the explanation of the monographs cited above will be discussed, but minor differences will not be referred to, because of lack of space and not because they have been overlooked.

A. Persistence of One or Both Pulmonary Arches

Abnormalities in the development of the pulmonary arches are rare, except the condition of persistence of the ductus arteriosus. This may be accounted for by supposing that this arch develops after the factors which produce the anomalies we have been considering have ceased to be operative. Bremer (1908) has shown that the truncus pulmonis absorbs a part of the pulmonary arches, so that the left pulmonary artery springs from the truncus while the right pulmonary artery represents in its proximal portion a part of the right pulmonary arch. This point should be kept in mind in interpreting cases of absence of the aortico-pulmonary septum like that of Clarke (1885).

Persistence of both pulmonary arches is very rare; the only cases with which I am familiar are those of Breschet (1826) and Peacock (1868). In the former the aortic arch was normal, the common pulmonary artery short and from its left branch the ductus arteriosus extended in the usual way. From the right branch of the pulmonary artery a slender artery extended upward to the right, joining the subclavian artery in its proximal portion.

In the latter case the development is not so regular; Breschet's case is illustrated in fig. 30.

Persistence of the right arch with atrophy of the left (ductus arteriosus) is not so unusual as persistence of both arches. When the development of the vascular arches is otherwise normal a right pulmonic arch (ductus arteriosus) may persist; it would seem that if the normal developmental relations are maintained it should join the proximal portion of the subclavian and represent in its distal part a segment of the right dorsal aorta. This would correspond to the position on the left or the position it occupies in cases of right arch persisting, Abernethy (1793); however in the cases of Gruber (1846), Jackson (1875) and Hildrith (1880) the vessel joins the innominate just before its division. The explanation of this condition presents some difficulties especially in the light of other anomalies of the arch.

A right arch persists occasionally in cases of right aortic arch, although this is not the rule: Abernethy (1793), Breschet (1826), Otto (1824), Ollivier (1861), Quain 1844) and Lockwood (1884). In these cases it passes from the right pulmonary to the aorta at a point below the origin of the right subclavian. In cases of situs viscerum transversus the left arch usually persists at least till birth, but in the cases of Arnold (1868) and Griffith (1891) the development of the right arch obtained as in the cases of right aortic arch above.

Persistence of the left arch to the time of birth and its later obliteration was known to Galen and its place in the foetal circulation was described by Harvey. The persistence of the arch, ductus arteriosus Botalli, is not a rare anomaly and it is frequently combined with other developmental defects, having to do particularly with the circulation of the lungs.

The cause of this anomaly has been sought indirectly in endeavoring to discover the process which produces normal occlusion. Two main factors have been suggested as responsible for the obliteration of the ductus arteriosus: (*a*) lowering of the blood pressure in the ductus after birth and (*b*) the difference in the histological structure in the ductus and the connecting blood-vessels. Recently Faber (1912) concluded that the obliteration

is due to stretching; this stretching occurs through the force of the left pulmonary artery being filled with blood. Stienon (1912) recognized the changed relations dependent on the establishment of the pulmonary circulation but thought that the ductus also becomes compressed by the expanding left lung.

Taking into consideration then the three theories of closure, *i. e.*, decreased blood pressure, absence of muscular fibers in the wall of the ductus and mechanical influences, a study of the cases in which the ductus remains open would suggest that more frequently a condition of pressure in the vessels, similar to that existing before birth, is the most important element although no doubt the other factors, or rather the disturbance of their action, may have an influence.

As indicated above the factors producing situs transversus and right aortic arch seem to have little influence on the development of the pulmonic arch and in these conditions when the ductus persists it may join the descending aorta, Dubrueil (1847), Chartier (1905),—or it may open into the left subclavian when that vessel is the last branch of the arch. This condition should not be confused with double aortic arch, for in both there is a vascular ring about the trachea and esophagus.

The following cases illustrate the union of the ductus with the left subclavian artery when it is the last branch of the arch:

Klinkosch (1766), Cailliot (1807), Obet (1808), Bernhard (1818), Hermann (1830), Ewen (1840), Greig (1852), Fick (1854), Tüngel (1862), Broader (1866), Cameron (1871), Combes & Christopherson (1884), Lane (1887), Riche (1897), Garnier & Villemin (1909).

Persistence of the left arch, ductus arteriosus Botalli, is not a wide departure from the normal and cases with or without other developmental anomalies in conjunction are numerous. Variation in the position of the distal end presents a point of some interest. Normally during development when the arch is formed it is joined to the dorsal aorta at a point slightly above the definitive subclavian artery; later in the adjustment of parts it is frequently found below the subclavian origin. It would seem that there has been a disturbance of the normal shifting process in those cases in which the ductus joins the subclavian artery instead

of the aorta, Reinemann (1754), Breschet (1826), Quain (1844), Pl. 7, fig. 2; see fig. 28, Bochdalek (1867).

A still more interesting variation is that in which the left subclavian artery is the continuation of the ductus and is entirely separated from the aorta, Holst (1832) and Hildebrand (1842). These cases have been incorrectly classed with that of Osler (1880) and others, see page 40, which have a very different basis for their formation.

Strassmann (1894) has very fully reviewed the subject of the patency of the ductus arteriosus, so it will not be necessary for me to review it farther, since no new details have been encountered. See figs. 27, 28, 30, 33 and 34.

The following references will illustrate the various conditions under which persistent ductus arteriosus is found and will suggest the frequency of occurrence:

Obet (1808), Langstaff (1811), Baillie (1812), Cailliot (1812), Farre (1814), Meckel (1816), Kreysig (1817), Tiedemann (1825), Breschet (1826), Bock (Cerutti 1827), Mauran (1827), Holst (1832), Chassenat (1836), Walshe (1842), Quain (1844), Beck (1846), Gruber (1846), Babington (1847), Chevers (1847), Crisp (1847), Peacock (1847), Bernutz (1849), Chevers (1851), Johnson (1851), Ward (1851), Hale (1852), Rokitansky (1852), Keil (1854), Willigk (1854), Luys (1855), Clar (1857), Langer (1857), Meyer (1857), Sturock (1859), Pannard (1860), Hervieux (1861), Ollivier (1861), Almagro (1862), Dúroziez (1862), d'Bary (1864), Rokitansky (1864), Schnitzler (1864), Ramsbotham (1865), Gerhardt (1867), Glas (1867), Arnold (1868), Walkhoff (1869), Peacock (1870), Semple (1870), Cameron (1871), Pye-Smith (1872), Fagge (1873), Jackson (1875), Martin (1877), Walsham (1877), Franck (1878), Allen (1879), Peacock & Reed (1880), Hildrith (1880), Lees (1880), Luneau (1880), Malherbe (1880), O'Sullivan (1880), Ingendahl (1881), v. Etlinger (1882), Holl (1882), Scott (1882), Abercrombie (1883), Thoma (1883), Ashby (1884), Berrand, Barry & Rachet (1884), Combes & Christopherson (1884), Coupland (1884), Foulis (1884), Holt (1884), Darier (1885), Vilon & Lévêque (1885), Barbillon (1886), Lane (1886), Leo (1886), Fussell (1888), Habershon (1888), Murray (1888), Hopkins (1889), Rickards (1889), Schanz (1889), Griffith (1891), Laffitte (1892), Moore (1892), Boquel (1893), Hebb (1893), Hochhaus (1893), Saunders (1893), Ferguson (1894), Haury (1894), Probyn-Williams (1894), Stembo (1894), Frenkel (1896), Monod (1896), Siredey (1896), Cyon (1897), Josefson (1897), Gérard (1899), Alfieri (1900), Gibson (1900), Thomson & Drummond (1900), Ardissonne (1902), Sidlauer (1902), Gutkind (1903),

Scheffer (1903), Schreiber (1903), Letulle (1904), Chartier (1905), Apert & Brézard (1906), Ellis (1906), Carpenter (1909), Weiss (1909), Wenner (1909), Robertson (1911), Variot & Moranci (1911), Hayashi (1912), Keith (1912), Gasquet (1913), Hebb (1913), Matzfeldt (1913), Milland (1914).

The following cases are considered from the diagnostic standpoint during life: Burghart (1898), Zinn (1898), Dressler (1902), Pfeifer (1902), Starck (1902), Arnheim (1903), Bittorf (1903), Hochsinger (1907), Wessler & Barss (1913).

B. Persistence of Both Fourth Arches

The persistence of the fourth right embryonal arch in conjunction with the left arch produces a peculiar and rare anomaly. If there is a maintenance of the early embryonal condition, fig. 5, the right, posterior, arch will pass over the right bronchus and give origin to the right subclavian and carotid arteries; the left, anterior, arch will be in somewhat near the normal position of the aortic arch and will give origin to the left carotid and subclavian arteries. The arches will join dorsally somewhat below the attachment of the ductus arteriosus and will thus form a complete vascular ring about the trachea and œsophagus.

The following cases may be classified under this head:

Hommel (1737), Biuni (1765), Malacarne (1784), Bertin (1824), Zagorsky (1824), v. Siebold (1836), Hyrtl (1841), Blandin (1842), Rendu (1842), Jones (1846), Cruveilhier (1851), Thomson (1863), Watson (1877), Shepherd (1880), McKee (1887), Heller (1904), Hamdi (1906), Gladstone & Wakeley (1915).

The case of Malacarne is somewhat irregular, fig. 26, and difficult to explain. The internal and external carotids come from the arch and probably represent an absence of the third arches. Hommel's case, fig. 27, seems to represent the typical condition. The case reported by Zagorsky consists of an anterior arch which is evidently the normal one and which gives origin to the innominate trunk and the left common carotid. The posterior trunk passes between the œsophagus and the trachea, giving off the left subclavian before joining the descending aorta. It is difficult to understand how, if this right vessel is the right arch, it reached the position in front of the œsophagus; on the other hand

to explain it as an aberrant vessel which through some need has reached the proportions of an aorta is to rob any vascular anomaly we do not understand of its embryonal significance and reaffirm the theory of Baader. This case is in some respects similar to that of Shepherd which is figured in the *Hand Book of Medical Sciences* as fig. 292. In the latter case however we must interpret the anomalous vessel as representing, in addition to the descending aorta, one of the segmental vessels and its root.

Thomson reported a condition which, while not a true arch, should be included in the classification as representing an intermediate condition. In a case of right aortic arch a fibrous cord occupied the position of the left descending aorta. A case referred to by Curnow (1875) is somewhat similar.

The case of Jones is very interesting as representing an arrest of development at a very early stage for not only do both arches persist but there are two dorsal aortae as well.

The description given by McKee is somewhat confusing, but it seems to me that this case should be interpreted as a case of right aortic arch, with anomalous blood supply to the lungs resulting from obstruction of the pulmonary trunk.

C. Persistence of the Right Aortic Arch with Partial or Complete Obliteration of the Left Fourth Arch

This condition is commonly spoken of as "right aortic arch" from which it might be concluded that the normal process of development is simply reversed on the two sides; however an examination of the cases shows a number of different conditions which fall into the following classes.

1. Persistence of the right arch, right dorsal aorta and left arch with obliteration of the left dorsal aorta.

2. Persistence of right aortic arch, left ventral root and left dorsal aorta with obliteration of the fourth dorsal root and arch on the left.

3. Persistence of the right aortic arch, left aortic arch and left dorsal aorta with obliteration of the left dorsal root.

4. Normal condition of the arches in a case of situs viscerum transversus.

1. I have placed this type first because it would seem to be most nearly a simple exchange of the two sides in the normal development, fig. 9. The arch passes over the right bronchus and gives off first the innominate, which passes to the left, dividing into the left common carotid and the left subclavian, then the right common carotid and the right subclavian. It continues downward as the dorsal or descending aorta and sooner or later assumes the normal position to the left of the bodies of the vertebrae. This condition is usual in situs transversus but is occasionally varied, Hickman (1869).

I have already shown, section II, *A*, that it is unusual in cases of right arch, or situs transversus, to find the ductus or ligamentum arteriosum on the right, from which we must conclude that the developmental factors for the two arches, aortic and pulmonary, are quite independent of each other or that the factors determining the normal type for the pulmonary arch are less easily influenced than the other. An examination of the ligamentum arteriosum in these cases shows that there are two different dispositions of its distal end. In one type there is a dilation of the aorta opposite the third or fourth dorsal vertebra, to which the duct or ligament is attached. This dilation represents the vestige of the left dorsal aorta, Thomson (1863), Dubrueil (1847), Plate II, fig. 1. In the other type the ligament joins the left subclavian a short distance from its origin, Bernhard (1818), copied by Quain '44 as Plate VII, fig. 3. In the latter type the proximal portion of the subclavian represents the dorsal root of the left fourth arch.

Examples of this class of right aortic arch are not numerous, see fig. 29. I have been able to find only the following:

Cailliot (1807), Bernhard (1818), Breschet (1826), Cruveilhier (1831), Quain (1844), Gruber (1846), Dubrueil (1847), Thomson (1863) 2 cases, Turner (1883), Vincenzi (1886), Reid (1914).

2. This condition is found much more frequently than the preceding; its development is easily understood by referring to

fig. 10. The arrangement of the branches from the arch is first the left common carotid, the right common carotid, the right subclavian and last the left subclavian artery. In that the left subclavian is the last branch of the arch and represents in its proximal portion the left dorsal aorta, it presents a close analogy to the condition of the right subclavian as the last branch, section II, *D*, 1.

This anomaly is not nearly so frequent as the low right subclavian, but when we compare it with the total number of right arches it is seen to be the usual type of development. It would seem that the tendency to develop is stronger in the left dorsal aorta than the left fourth arch and that when disturbing factors produce this irregularity they more readily affect the arch or they act with greater force on the arch, and the persistence of the right dorsal aorta may be looked upon as an arrest of the normal atrophic process to compensate for the obliterated canal. In the case of the low right subclavian, some disturbing factor causes an obliteration of the fourth right arch when there is an arrest of the normal atrophic process in the right dorsal aorta to compensate for this obliteration of the canal and insure a circulation to the extremity. If it is correct to view the two conditions in this light the anomalies are similar in that in each case some factor or factors causes the obliteration of an arch which normally develops and a compensating development of the right dorsal aorta occurs, see figs. 28 and 32.

The following cases are representative of this type of anomaly:

Klinkosch (1766), Schleitz (1768), Fiorati (1786), Sandifort (1793), Obet (1808), Meckel (1809), Meckel (1816), Otto (1824), Hermann (1830) 2 cases, Pommer (1840), Hyrtl (1841), McWhinnie (Quain '44), Quain (1844) 3 cases, Ewen (1845), Tiedemann (1846), Paetruban (1848), Greig (1852), Fick (1854), Meyer (1857), Schwegel (1859), Agliette (Peacock '60), Peacock (1860), Tügel (1862), Turner (1862), Gruber (1863) 2 cases, Broader (1866), Bochdalek (1867), Barkow (1869), Cameron (1871), Watson (1877), Pertik (1880), Brenner (1883) 2 cases, Combes-Christopherson (1884), Lockwood (1884), Dittrich (1886), Gottschau (1887), Lane (1887), Lockwood (1890), Herringham (1891), Abbott (1892), Lunn (1896), Riche (1897), Brachet (1908), Annan (1909).

Garnier & Villemin (1909), Macalester (1909), Weiss (1909), Dickson & Frazer (1914), Reid (1914), Warren Museum 1 case.

3. This group of cases would be representatives of double aortic arches except for the absence of the left dorsal root; the order of branches is a left innominate stem dividing into left common carotid and left vertebral, right common carotid, right subclavian and left subclavian. The condition is recognized by Piersol in his anatomy and figured as fig. 688; he suggests that it is the reverse of fig. 685 (our II, D, 2) but he does not label the left vertebral in the figure.

Brenner (1883) first explained this condition and showed the relation of the inferior laryngeal nerve to the left vertebral artery; he expressed the idea of a "widening" of the vertebral but now we know from Hochstetter's work (1890) that the vertebral and subclavian represent different segmental vessels. Brenner's case is figured Taf. 17, fig. 5, our fig. 11, and contains the additional variation of a right vertebral springing from the arch between the right common carotid and right subclavian.

4. Of this group we also have only one example, that of Fox (1824) which presents a normal arrangement of the vascular arches in a case of complete situs viscerum transversus. It may be viewed as a reversal of group 1 above, considering the body as a whole; on the other hand it is interesting in the suggestion that the factors which produce situs transversus may not always be operative in the development of the arches.

For other variations in cases of right aortic arch belonging to origin of vessels springing from the arch see III, B, 2, g; C, and II, D, 2, g.

D. Abnormal Obliteration or Persistence of Segments of the Arches or Dorsal Roots

A number of more or less limited irregularities of development are included in this section. They are grouped in this way not because they are morphologically similar, for they represent very divergent patterns, but because they represent circumscribed or local effects of the factors which have disturbed the normal course

of development. As already pointed out, objections to this arrangement are appreciated and more data or a different viewpoint might suggest an entirely different classification.

1. Right fourth arch obliterated, right dorsal root persists and is represented in the right subclavian, which is the last branch from the arch.

2. Right fourth arch persists and is represented in the proximal portion of the right vertebral, right dorsal root persists and is represented in the beginning of the right subclavian.

3. Right fourth arch persists and is represented normally, the right dorsal root is present and is represented in the proximal portion of the right vertebral.

4. Obliteration of the fourth left arch and dorsal connection with the fifth arch, persistence of the left pulmonary arch.

5. Obliteration of the dorsal connection between the fourth and pulmonic arches, persistence of the left pulmonary arch.

6. Obliteration of the right third arch, persistence of the dorsal connection between the third and fourth arches.

7. Obliteration of the third left arch, persistence of the dorsal connection between the left third and fourth arches.

8. Obliteration of the third arch and dorsal roots beyond.

1. Right fourth arch is obliterated, right dorsal root persists and is represented in the right subclavian artery, which is the last branch of the arch.

- (a) Cases in which the right subclavian passes between the œsophagus and vertebral column.

- (b) Cases in which the right subclavian passes between the trachea and œsophagus.

- (c) Cases in which the right subclavian has a pretracheal course.

- (d) Cases in which this anomaly is seen in conjunction with irregularities in arrangement or number of branches springing from the arch.

- (a) The origin of the right subclavian artery from the descending aorta is not a rare irregularity but perhaps on account of its unusual appearance it has received more attention than any other anomaly considered in this paper. The major portion of

cases consist of a normal aortic arch giving rise to the right common carotid, the left common carotid and the left subclavian arteries, while the right subclavian springs from the descending aorta on its dorso-lateral aspect opposite the second or third dorsal vertebra, and passes behind the cesophagus to reach its normal position.

The condition was first explained developmentally by Wood (1859), who recognized it as a persistence of the right dorsal aorta, fig. 12, represented in the proximal portion of the subclavian. The frequency of the condition is variously estimated as illustrated by the following:

Name	Per cent	No. Cases Observed
Quain (1844) .....	.4	212
Tiedeman (1846) .....	.8	
Turner (1862) .....	.4	
Thomson (1863) .....	.6	800
Thomson (1891)	1.	500
Leboucq (1894) .....	.5	
Stieda (1894) .....	.8	
Götz (1896) .....	.8	
Adachi (1914) .....	.3	271

While the first cases were all grouped together in one class when they were analyzed, Holzapfel (1899), it was seen that they are not all alike, but fall into different classes, as I have indicated above. These cases have been explained from the developmental standpoint so frequently that it will not be necessary to repeat such explanations here; also reference to fig. 12 will make the point clear. It seems to me that one point should be emphasized in the developmental side of these anomalies; from a study of right aortic arch, see page 30, and comparing those anomalies with this one there is a strong suggestion that the important feature of the irregularity is not the persistence of the dorsal root but the obliteration of the right fourth arch. In looking for the etiology of the condition we should seek a factor or factors acting abnormally on the arch.

During the past year a case of this type was encountered in our dissecting rooms, the first in 150 bodies, which is in every way

typical of the class; I will describe it here both to report the case and to illustrate the type.

Specimen is from a man 62 years old who died of Bright's disease; he did not suffer from *dysphagia luxoria* and was not left-handed. Fig. 25 was drawn from the dissection.

The heart was normal, the aortic arch was normal in position and size, it gave off first the right common carotid, the left common carotid, the left subclavian and last the right subclavian. The latter vessel arose from the right dorsal aspect of the aorta opposite the juncture of the bodies of the third and fourth dorsal vertebrae, passed behind the oesophagus upward, describing a slight curve with the convexity to the left, to reach its usual position in relation to the scalenus anticus muscle. The right vertebral artery, which was the first branch given off, had the usual relations and entered the sixth costo-transverse foramen. The ligamentum arteriosum was normal and was attached to the aorta about 3 cm. above the origin of the right subclavian.

The recurrent laryngeal nerve on the right was given off in the neck and passed almost directly across to the trachea without making any downward loop. The thoracic duct divided into two trunks, of which the right was slightly the larger, opposite the fifth dorsal vertebra and emptied into the venous angle on both the right and left sides. There were no other anomalies observed in the entire body.

There are seven similar cases in the Warren Museum, which I examined and which, I believe, have not been reported. In two of these there is a definite dilation at the point where the subclavian leaves the aorta; the other cases are in no wise remarkable and all are without history.

Cases of this type are most numerous, see figs. 39 and 41, and present a simple developmental disturbance which is entirely compensated for and consequently works no ill to the individual. I have been able to collect the following cases, referring freely to Holzapfel's (1899) splendid work:

Hommel (1737), Cassebohm (Böhmer 1741), Hoffmann (1751), Mieg (1753), Löseke (1754), Ludwig (1764), Schleitz (Ref. Murray 1768), Erdmann (1772), Sandifort (1772), Pohl (1773), Walter (1785), Cruickshank (1789), Hulme (1789), Valentin (1791), Sandifort (1793), Isenflamm (1800), Meckel (1805) 4 cases, Autenrieth & Pfeleiderer (1806) 2 cases, Koberwein (1810), Zagorsky (1810), Isenflamm & Fleischmann (1815), Meckel (1816) 3 cases, Otto (1816), Kirby (1818), Colles (1820) 4 cases, Meckel (1820) 2 cases, Tiedemann (1822), Stedman (1823), Godman (1824), Hesselbach (1824), Hart (1826), Cerutti (1827), Mayer (1827), Wagner (1828) 2 cases, Weber (1829) 2 cases, Green (1830) 3 cases, Hopkinson (1830), Lauth (1830), Otto (1830) 6 cases, Cruveilhier &

Lenoir (1832), Fleischmann (1835) 2 cases, Dubrueil (1837) 2 cases, Harrison (1839) 2 cases, Liston (1839), Todd (1839), Demeaux (1841), Gorgone (1841) Ref. Banchi '07, Brent (1844), Patruban (1844), Quain (1844) 8 cases, Reid (1846) 2 cases, Arnold (1847), Demarquay (1848) 3 cases, Stachelroth (1850) 2 cases, Frandsen (1854), Cavasse (1856), Hyrtl (1859), Oehl (1859) 2 cases, Wood (1859), Peacock (1860) 5 cases, Dubrueil (1862), Turner (1862) 4 cases, Barkow (1866), Barwell (1867), Wood (1867), Barkow (1869) 10 cases, Bankart, Pye-Smith, Phillips (1869) 2 cases, Peacock (1870), Bradley (1871), Eppinger (1871), Leidy (Ref. Mears '71), Mears (1871), Pancoast (Ref. Mears '71), Pye-Smith, Howse, Davies-Colley (1871) 2 cases, Düben (1876), Krause (1876), Shepherd (1877), Zenker (1878) 5 cases, Flesch (1879), Carrier (1880), Walsham (1880), Wiltshire (1881), Brown (1882), Giacomini (1882) 6 cases, Brenner (1883) 3 cases, Ozenne (1883), Horrocks, White, Lane (1884), Collins (1885), McArdle (1885), Beisso & Giuria (1886) 3 cases, Struthers (1888), Deaver (1889), Mann (1889), Calori (1890) 5 cases, Dunn, Washburn, Targett (1890), Ledouble (1890) 3 cases, Rau (1890), Thomson (1890), Bothezat & Chatinière (1891), Thomson (1891) 3 cases, Solger (1893), Leboucq (1894) 4 cases, Faure (1895), Jacques (1895) 2 cases, Götz (1896) 2 cases, Testut (1896) 2 cases, Herrick (1897), Miura (1897), Anile (1898), Holzapfel (1899) 4 cases, Rolly (1899) (Ref. Banchi '07), Hamann (1900), Ledouble (1901) 3 cases, Blair (1902) 2 cases, Cabibbe (1901) (Ref. Banchi '07), Bouchet (1903), Duckworth (1906), Gérard (1906), Gianelli (1894) (Ref. Banchi '07), Zoia (1872) (Ref. Banchi '07), Banchi (1907), 2 cases, Pearce-Gould (1909), Geddes (1910), Hasebe (1912), Adachi (1914), Cobey (1914), Gladstone & Wakeley (1915), 7 cases in the Warren Museum.

This irregularity is very unusual in animals but the following cases have been encountered.

Meckel (Ref. Cuvier 1810) in the hedgehog, Ogilvie & Cathcart (1874) in a lamb and Smith (1891) in a rabbit.

(b and c) The condition in which the anomalous subclavian is between the cesophagus and trachea and that in which it is in front of the trachea may be considered together from a developmental standpoint, but the cases of each type will be listed separately. Fig. 5 may be used to illustrate the conditions but not to suggest the actual developmental process. There are many difficulties in the way of using the explanation which accounts for the formation of the preceding group (fig. 12) in expounding the formation of these irregularities; neither Turner (1862) nor Krause (1876) seem to have fully appreciated the fact.

Several hypotheses have been offered in explanation of the ventral position of the proximal portion of the subclavian but none of them, it seems to me, are entirely without objection. The first assumes that the dorsal aortae unite ventral to the œsophagus. Such a process is difficult to understand in view of the way in which the common aorta normally develops; then too if a process so fundamental, apparently, as aortic development may present such an extreme irregularity we have no evidences of its having been found except in this one anomaly and always at this point.

The second hypothesis, that of Rau (1890), offered as an explanation of the general class, conceives that the anomalous subclavian has arisen by early anastomoses with the right bronchial artery. This would account for the ventral position of the vessel, but we would have to assume a very high origin for the bronchial and also that it developed much earlier than it seems to do normally. The right bronchial artery would then be a branch of the anomalous subclavian and no such condition has been reported (Holzapfel).

The third hypothesis, which is favored by Holzapfel (1899), is that an anomalous anastomosis develops ventrally between the paired descending aortae. This anastomosis occurs early, then when the lungs are laid down their relation to this aberrant vessel will determine which type, *i. e.*, *b* or *c*, will develop. The explanation cannot be disproved but may be objected to on the ground that it denies an orderly development of the earliest vascularanlage and reaffirms the theory of Baader for this particular anomaly, in the light of all the more recent investigations which suggest that a more exact explanation may be possible.

The fourth hypothesis was offered by Banchi (1907) who thinks these cases represent a persistence of both fifth (not pulmonary) arches with atrophy of the dorsal root of the right fourth arch and the right descending aorta. We may offer as an objection to this that there is possibly still some controversy on the "fifth" arch, see page 8, but more important, that such an explanation necessitates an anomalous union between these arches ventrally, which is as great a difficulty as the general question; or if we accept his explanation of this point we still have to account

for an atrophy of the junction of the "fused" fifth arches and the ventral aortae, see fig. 7.

The following cases represent the two conditions: *b*, cases in which the anomalous subclavian passes between the œsophagus and the trachea; *c*, cases in which the subclavian passes ventral to the trachea:

Group b (artery passes between trachea and œsophagus): Bayford (1789), Brewer (1791), Monro (1797), Herold (1812), Hesselbach (1824), Harrison (1839), Hyrtl (1841), Pigné (1847), Stachelroth (1850), Gross (1852), Peacock (1860), Brown & Brown (1868), Bankart, Pye-Smith, Phillips (1869), Bradley (1871), Calori (1890), Thomson (1891), Gladstone & Wakeley (1915).

Group c (artery is pretracheal): Hunauld (1735), Meckel (1751) in a letter to Haller (1743-56), Walter (1785) 2 cases, Cruveilhier (1831), Vittorini (1831) (Ref. Banchi '07), Dubrueil (1847), Blandin (1842), Burns (Ref. Banchi '07).

Another question in connection with these cases, which is of great interest, is the relation of the right vagus nerve to the anomalous subclavian artery. Unfortunately many reports are silent on this point but it is shown from the reports recording this relation that in some cases the nerve runs ventral to the artery and in others it has a dorsal course. Banchi (1907) suggests that the process by which the nerve reaches a dorsal position in these cases is through a secondary subclavian, which Rabl (1906) has shown is the manner in which a similar relationship is effected normally in birds.

(*d*) In certain cases of anomalous subclavian artery there are additional variations either in the number of branches springing from the arch or in their position on the arch. It is my impression from a study of these cases in conjunction with other variations that they represent two independent processes; they are included here as a separate group simply to facilitate more detailed study. The cases are all listed in the preceding groups of this class and are again listed in the proper classes under section III, so in the following list references for full detail are to the various classes of section III.

Hunauld (1735), Meckel & Haller (1751), Erdmann (1772), Sandifort (1772), Walter (1785), Koberwein (1810), Meckel (1820), Tiedemann

(1822), Godman (1824), Wagner (1828), Green (1830) 2 cases, Lauth (1830), Dubrueil (1837) 2 cases, Demeaux (1841), Brent (1844), Quain (1844) 5 cases, Tiedemann (1846) 4 cases, Pigné (1847), Cavasse (1856), Barkow (1866), Wood (1867), Barkow (1869) 3 cases, Bankart, Pye-Smith, Phillips (1869) 2 cases, Pye-Smith, Howse, Davies Colley (1871), Carrier (1880), Giacomini (1882) 2 cases, McArdle (1885), Brodie (1888), Shepherd (1890), Thomson (1891), Abbott (1892), Leboucq (1894), Jacques (1895), Götz (1896), Herrick (1897), Holzapfel (1899) 4 cases, Banchi (1907), Warren Museum 5 cases.

For the detailed classification of the cases in this list see the following sections: III, *B*, 2, *c*; III, *C*, 4; III, *C*, 6; III, *D*, 1, *d*; III, *D*, 1, *g*; III, *D*, 1, *h*; III, *D*, 1, *k*; III, *D*, 2, *b*; III, *D*, 2, *d*; III, *D*, 2, *e*.

2. The right aortic arch is present and is represented in the proximal portion of the right vertebral artery, which seems to spring from the right common carotid. In this group conditions are the same as in group 1, except that the right vertebral springs from the right common carotid instead of from the right subclavian artery. Reference to fig. 13 will explain the method of development of the irregularity. The theory of its occurrence was first suggested by Brenner (1883) and was based on the relation of the right recurrent laryngeal nerve. This has the same relation to the vertebral artery in these cases as it bears normally to the subclavian artery of this side. It will be seen that this theory necessitates considering that the vertebral has an origin in a higher segmental artery than the subclavian, but, as is pointed out in considering the development of the vertebral, page 10, this is not unreasonable. It would seem that the disturbing developmental factors have affected just the connection between the sixth and seventh segmental arteries and the right dorsal aortic root; or perhaps the primary defect was in the connection between the segmental arteries, and the resulting anomalies, *i. e.*, persistence of the sixth segmental artery and the right dorsal aorta, are in the nature of compensation for this irregularity of development, see fig. 39.

The following cases belong to this group:

Murray (1768), Green (1839), Simon (1846), Tiedemann (1846), Dubrueil (1847), Hyrtl (1859), Wood (1859), Brodie (1888), Shepherd (1890), Abbott (1892), Solger (1893), Suzuki (1894), Holzapfel (1899), Kemmettmüller (1911) 3 cases, Hasebe (1912).

3. This group presents a persistence of the right dorsal aorta represented in the proximal portion of the right vertebral artery; for diagram see fig. 14. The branches of the arch are normal, but the right vertebral, instead of springing from the subclavian in the usual manner, arises from the descending aorta just below the arch, passing outward and upward behind the subclavian to reach its normal position. In these cases the vertebral originates through a lower segment than the subclavian and in this respect is the reversal of group 2. If there were no other change than the persistence of the two segmental arteries and the right dorsal aorta the picture would be one of a double arch. The fact that the right arch includes a connection between the two segmental arteries instead of the right fourth root could not be appreciated from an examination of the case.

It seems to me that to explain these cases we must assume that the axillary plexus, page 10, which Göppert has shown is always present, early makes a connection with one of the upper segmental arteries, say the sixth, very near its origin from the aorta. With this pathway established the more distal portion of the segmental (sixth) atrophies; then, when the connections are established between the segmental arteries to make up the vertebral, either a more cephalic segmental will furnish the origin of the vertebral or a more distal one (seventh); in the former condition the vertebral may arise from the subclavian near the common carotid and enter a higher transverse foramen, Waldeyer (1909), or from the common carotid as in one of Brenner's (1883) cases where it entered the fourth transverse foramen; in the latter, representing this group, the persistence of the right dorsal aorta is in compensation for the absence of other vertebral connections. The vertebral enters the seventh or sixth foramen.

The following cases representing the condition have been reported:

Hyrtil (1859) 2 cases, Struthers (1875), Paterson (1884), Azuta (1905), Szawłowski (1906).

4. Obliteration of the fourth left arch and dorsal root, persistence of the left pulmonary arch. In these cases the innomi-

nate and left common carotid spring from the ventral aorta and represent the circulation from the left side of the heart. The ductus arteriosus is patent and joins, or is continuous with, the descending aorta; at the angle formed by the two the left subclavian artery is given off, see fig. 15. It seems most logical to account for these cases as due to disturbance with the development of the left arch; in this respect they are closely allied to cases of the more numerous type of right aortic arch, II, C, 2; however it seems to me that probably the disturbing factor acted at a later period than it did on the right arches, *i. e.*, after the normal atrophy of the right dorsal aorta had been effected. As already indicated these cases present a different problem of developmental disturbance than the case of Holst, page 26.

Greig (1852), Struthers (1875), Osler (1880).

5. Obliteration of the dorsal root of the left fourth arch, persistence of the left pulmonary arch. This condition is evidently closely related to the preceding group. The innominate, left common carotid and left subclavian are normal, the left arch terminates with the left subclavian and the descending aorta is continuous with the left pulmonary through the ductus arteriosus. This condition seems to bear the same relation to II, C, 3 that the preceding one does to II, C, 2. The disturbing developmental factor acts on a limited area, the left fourth dorsal root, but this same local effect is seen in II, C, 3, II, D, 2 and II, D, 3, see fig. 16.

I know of only one example of this anomaly, the case of Steidele (1778). Valenti & Pisenti (1896) have reported a case which is suggestive of the condition although the obliteration is not quite complete; probably also some of the cases of coarctation of the aorta, which is not considered in this paper, are examples of the less pronounced effect of the same developmental disturbance.

6. Obliteration of the right third arch, persistence of the third right dorsal root.

7. Obliteration of the left third arch, persistence of the third left dorsal root.

Groups 6 and 7 may be considered together, since they are

identical except for the side affected. In each the common carotid is absent and the internal and external carotids spring from the arch. We may consider that the developmental disturbance leading to an atrophy or failure in development of the third arch is the primary condition and that the persistence of the dorsal root is an attempt at compensation for this anomaly, see fig. 17.

The following cases are illustrative of the two groups:

Group II, *D*, 6. Malacarne (1784) double arch, same condition on each arch, Power (Ref. Quain '44), Kosenski (1867), Macalester (1886), case I.

Group II, *D*, 7. Malacarne (1784), double arch; Gottschau (1885); Macalester (1886), case II; v. Augenmayer (1906), Siegfried (1906).

8. Obliteration of the third arch and the roots beyond. This condition is characterized by the absence of the internal carotid; the condition may occur on either the right or left side and to make the classification uniform with the preceding should be divided into two groups, one for each side.

Absence of the external carotid is less frequent but does occur, Langenbeck (1841).

All of the following cases are failure of development on the left side except that of Todd, which is on the right and Fisher, which is on both sides.

Todd (1787), Koberwein (1810), Quain (1844), Peugnet (1876), Wyeth (1878), Flemming (1895), Fisher (1914).

§ VII

III. IRREGULARITIES IN DEVELOPMENT OF BRANCHES OF THE AORTA

This section will include, in addition to the variations in number and arrangement of branches springing from the aortic arch, anomalous arteries of the ascending aorta. Some of these conditions are understood embryologically, but many of them are still without satisfactory explanation from a developmental standpoint; consequently, instead of classifying them from a developmental standpoint, as has been done in the preceding sections, a simple morphological classification will be followed. The arrangement of branches in many of these groups is similar to type forms in other mammalia. It is interesting to note that through

all classes of mammals there is variation in the arrangement of branches from the arch in the individual species. No single species or genus shows a wide variation till primates are reached, and man seems to present as anomalous development all of the conditions encountered in other mammalia. I have already reviewed, see page 11, the significance of the comparative anatomy, so it will only be necessary here to repeat that in citing under the various groups the animals presenting the same condition normally it is done simply as a point of morphologic interest and not with the idea of suggesting an atavistic relationship.

Some of the variations already included in the preceding sections will be repeated here; this applies particularly to II, D, 1. This seems necessary because the basis of classification for this section is different than for the preceding and it is desirable to present together all of the examples of a given type of variation.

A. Irregularities in the Branches from the Ascending Aorta

1. *Irregularities of the Coronary Arteries.*—The coronary arteries exhibit several irregularities; of these the most frequent is the presence of one or more accessory arteries. Symmers (1907) reported these present in 40 percent of cases and that they were more frequently present on the right side. This is greatly in excess of the percentage present in the series reported by Halbertsma (1863) and Banchi (1904); the latter finds that when a third branch is present it is generally a branch of the right coronary, which has a separate origin from the aorta. In a hundred observations I have found in two instances that the area usually supplied by the right coronary was furnished by two short trunks direct from the aorta; this confirms Banchi's observation.

One artery may be absent and in that case the other artery supplies the entire heart.

The arteries, one or both, may arise higher than normal from the aorta, as in the cases reported by Farre (1814), Mayer (1827), Hyrtl (1841) and Chevers (1851).

Arteries multiple: Morgagni (1761), Meckel (1817), Halbertsma (1863), Krause (1865), Brooks (1885) from pulmonary, Hepburn (1886), Banchi (1904-7), Symmers (1907).

One artery: Fantoni (1699), Thebesius (1716), Mayer (1827), Otto (1830), Hyrtl (1841), Hyrtl (1855), Heitz (1901).

2. *Other Arteries from the Ascending Aorta.*—Bremer (1912) has shown that the ventral aorta is developed from a plexus and it seems probable that it is through the persistence of some of these early channels in connection with the aorta that such anomalies as the following are to be explained. That they are so very rare may be accounted for on the ground that this plexus is a very early formation, and is in a center of great growth activity and shifting of parts; any minor channels which might persist after the ventral aortae were established would almost certainly atrophy through pressure and lack of definite area to supply.

Thymic vessels springing from the ascending aorta have been reported by Haller (1747), Breschet (1826) and Hyrtl (1841).

Twice the internal mammary dextra has been observed arising from the ascending aorta. Such an anomaly is more difficult to reconcile with the above explanation unless we assume that the aberrant vessel of the plexus communicates with a segmental below the definitive subclavian, which in turn gives rise to the internal mammary; such a conclusion is not warranted by any developmental history of the internal mammary or any of its anomalies with which I am acquainted. The cases are reported by Böhmer (1741) and Meckel (1816).

B. Number of Branches from the Aortic Arch Less than Normal

1. One branch from the arch.

2. Two branches from the arch.

1. In these cases one branch springs from the arch of the aorta; see fig. 37. This condition is common in some of the lower mammals; the single branch divides into brachial and cephalic trunks which are arranged normally. The cases of this irregularity are not all exactly similar; in some the arch is apparently lacking and the descending aorta seems to curve over the bronchus from a junction with the ascending stem from its proximal portion; in other cases a stem springs from the top of the arch and almost immediately divides into the regular branches, suggesting that

they have simply migrated to a common point of origin. I know of no exact explanation for this irregularity; it is not difficult to account for the fusion of the left carotid with the innominate trunk, but if the arch is normal the anomalous position of the left subclavian is more difficult to explain.

The following cases of this irregularity have been reported:

Troussières (1667), Garnier, Spon & Troussières (1729), Haller (1768) (Ref. Meckel 1816), Klinz (1787), Meckel (1816), Boudant (1829), Hyrtl (1841-59), Dubrueil (1847), Vernon (1856).

This type of development is found in the following mammals: Antilopidae, atherura, bos, capra, cervus, dasyprocta, equus, gazella, genetia, rangifer, rhinoceros, tapirus.

2. Only two branches from the arch. This condition is represented by a number of different types of arrangement which have been classified as follows:

(a) Fusion of the ventral aortic roots or migration of the left carotid furnishes an innominate stem with the left carotid springing from it and the left subclavian arising from the arch, figs. 31 and 36. The positions of the right subclavian and carotids on the innominate present a number of variations; the left carotid may arise from the base of the innominate or a trunk may continue for some distance after the right subclavian is given off, then divide into the right and left carotids; for these various arrangements see Keith (1895) and Parsons (1902). These cases are numerous; Quain says twenty-five times in 219 cases, which probably explains why the older anatomists considered the condition normal. Vesalius figured the condition on pages 483 and 564.

The following list is given of references encountered during this study; it is evidently in no way representative of the number of times this condition has been observed; Thomson's report (1893) and Adachi's figures (1914) show a frequency of over 10 percent. I have observed the condition only twice in my dissecting rooms; in both of these cases and also in the two from the Warren Museum, reported below, the left carotid arose from the innominate trunk quite near its base; see fig. 36.

Vesalius (1543), Casserius (1609), Spegelius (1627), Vestingus (1641), Troussières (1668), Eustachius (1714), Heister (1717), Hunter (1717), Petsche (1736), Neubauer & Erdmann (1772) 2 cases, Meckel (1774), Huber (1777), Malacarne (1784), Neubauer (1786), Walter (1785), Burns (1809), Ryan (1812), Tiedemann (1822), Baron (Lauth 1825), Weber (1829), Lauth (1830), Hyrtl (1841), Quain (1844), Isaacs (1855), Kelly (1871), Peacock (1871), Pye-Smith, Howse, Davies, Colley (1871), Embleton (1872), Davies, Colley, Taylor (1873), Broca (1880), Shepherd (1880), Horrocks, White, Lane (1884), Deaver (1889), Freyberger (1898), Cowan & Ferguson (1903), Adachi (1914), Warren Museum 2 cases.

This condition is quite common in mammals; it seems to have been encountered occasionally in all of the primates and is probably the normal condition for Hylobates. It is the most frequent arrangement in the carnivores and has been noted in the following ungulates: giraffa, hippopotamidae, hyracidae, llama, suidae, tapirus. Among the rodents this type of arrangement is normal for lepus and has been reported for caviidae, hystricidae, lagostomus, myopotamus, octodon, sciuridae.

(b) This group may be termed bi-innominate; there are two trunks arising from the aortic arch and each divides into a subclavian and a carotid artery. The obvious anomaly is that the origin of the left subclavian has moved proximally on the arch till it is fused with the left carotid or that there has been a disturbance in the development of that portion of the arch between the carotid and subclavian. I have not been able to find any report of work on the developmental side of this problem.

The following examples have been reported; for illustration see fig. 35.

Biumi (1765), Malacarne (1784), Jackson (1816), Tiedemann (1822), Boudant (1829), Patruban (1844), Dubrueil (1847), Cruveilhier (1851), Broca (1880).

The bi-innominate trunks are normal for Chiroptera (Grosser 1901) and are frequently found in the following other animals: cetacea, chrysochloridinae, erinaceidae, tulpa.

(c) A condition of two branches from the arch, the first made up of the two carotids and the other of the two subclavians. There may be some doubt about these cases; only two have been reported, the first, Schön (1823), was referred to by Meckel in his anatomy (1817), page 111, as a case of bi-carotid bi-subclavian trunks, but Krause doubts the validity of the case; the

second, Patruban (1844), is accepted by Krause, but Holzapfel considers this a case of low origin of the right subclavian and a bi-carotid trunk; this seems to me the correct interpretation of the case.

(d) This group is similar to (a) except for a slight modification; the first trunk divides into the right subclavian, right and left common carotids and the right internal mammary; the second trunk from the arch is the left subclavian. I know of only one example, that reported by Hyrtl (1841).

(e) This group is like the one immediately preceding except that a thyroid ima takes the place of the internal mammary. Cases have been reported by Isaacs (1855), Paterson (1884) and Freyberger (1898).

(f) In these cases there are two branches from the arch, one an innominate trunk made up of the right and left common carotids and the left subclavian, the other trunk the right subclavian. Only three examples are available; viz., Zagorsky (1809), Breschet (1826) and Dubrueil (1847). These cases are quite difficult to interpret. Krause classified Zagorsky's case as one of right arch, although there was no mention made in the original of the direction of the arch; Tiedemann figured it, Plate IV, fig. 8; there was no figure in the original, and Quain copied his figure on Plate VI, fig. 8. It seems to me that instead of interpreting these as cases of right arch we might consider them as the counterpart of the next group.

(g) In this group the right aortic arch takes the place of the left; from the arch proper one trunk is given off, which divides into the left common carotid, right common carotid and right subclavian, from low on the arch, *i. e.*, the descending aorta, the left subclavian arises. This condition has been reported by Henle (1843), Tiedemann (1846) and Dubrueil (1847).

C. Number of Branches from the Aortic Arch Normal in Number but Abnormal in Arrangement

1. Order of branches, innominate trunk made up of right subclavian, right common carotid, left common carotid, then left

vertebral and last left subclavian, illustrated by fig. 43. In this group the innominate stem presents the same anomalous development that has been discussed in section III, *B*, 2 (*a*), the only difference from that section is the presence of a vertebral arising from the arch instead of in its usual position. This latter variation is brought about by the persistence of one of the higher segmental arteries and the failure to establish the normal connection with the segmental, which is represented in the subclavian; see fig. 6.

The following cases are illustrative:

Sandifort (1781), Walter (1785), Meckel (1816), Tiedemann (1822), Paterson (1884), White, Lane, Price (1883), Warren Museum.

2. This group is the same as the preceding except that the order of the subclavian and vertebral is changed; order of branches, innominate, left subclavian, left vertebral. Walter (1796 and 1805) reported a case, also Tiedemann (1822). Owen (1868) says the condition is normal for the giraffe.

3. Order of branches, right subclavian, common trunk for the carotids, left subclavian; illustrated by fig. 40. Cases are reported by Portal (1803), Tiedemann (1822), Dubrueil (1847), Trèlat (1856). This condition is found occasionally in elephants and some marsupials.

4. Order of branches, bi-carotid trunk, left subclavian and last right subclavian; illustrated by fig. 38. This arrangement of the carotids is a frequent one in the cases in which the right subclavian is the last branch of the arch.

The following list is taken from cases already reported in section II, *D*, 1, but repeated here because in the former classification the arrangement of the carotids was not indicated.

Hunauld (1735), Hommel (1737), Meckel (1751), Erdmann (1772), Sandifort (1772), Walter (1785), Green (1830), Lauth (1830), Demeaux (1841), Quain (1844), Patruban (1844), Dubrueil (1847) 2 cases, Pigné (1847), Stachelroth (1850), Cavaise (1856), Barkow (1866), Wood (1867), Brown & Brown (1868), Bankart, Pye-Smith, Phillips (1869), Barkow (1869) 2 cases, Bradley (1871), Carrier (1880), Giacomini (1882), Calori (1890), Herrick (1897), Thomson (1891), Leboucq (1894), Jacques

(1895), Götz (1896), Holzapfel (1899), Banchi (1907), Gladstone & Wakeley (1915), Warren Museum 5 cases.

5. The order of branches is: Bi-carotid stem, right subclavian, left subclavian. Cases reported by Lauth (1830) and Quain (1844).

6. The order of branches is: Right carotid, stem composed of the left carotid and the left subclavian, right subclavian; see fig. 41. One case has been observed by Tiedemann (1822); this belongs in the general class of low origin of the right subclavian, section II, *D*, 1.

7. The order of branches is: Innominate, left subclavian, left carotid. Example reported by Weber (1829).

8. The order of branches is: Innominate, left external carotid, left subclavian. This group has been previously reported as section II, *D*, 8.

9. The order of branches is: Innominate, dividing into right subclavian, internal and external carotids, left common carotid, left subclavian. Previously reported, see section II, *D*, 6.

10. In right aortic arch the order of branches is: Innominate (left), right carotid, right subclavian. Previously reported as Section II, *C*, 1.

11. In right aortic arch the order of branches is: Innominate made up of the right and left common carotids, right subclavian, left subclavian. This is the counterpart of group 4 above; cases, which are included in section II, *C*, 2, have been reported by Annan (1909) and Macalester (1909).

12. The order of branches is: Right subclavian, right carotid, left carotid from the arch; the left subclavian from the ductus arteriosus. Reported by Holst (1832) and Hildebrand (1842).

13. Ascending aorta divides into the right subclavian, right and left common carotids; the left subclavian and descending aorta from the ductus arteriosus. Reported as section II, *D*, 4.

D. Number of Branches from the Aortic Arch Greater than Normal

1. *Number of Branches Four.*—(a) The order of branches is: Right subclavian, right common carotid, left common carotid, left

subclavian (absence of innominate). The following cases have been reported:

Bergerus (1698), Heister (1717), Nicolai (1725), Winslow (1732), Pal-fyn (1734), Ballay (1758), Meckel (1809 and 16), Ryan (Monro 1813), Fleischmann (1815), Tiedemann (1822), Lauth (1825), Pitcard (1840), Isaacs (1855), Krause (1865).

(b) The order of branches is: Right common carotid, right subclavian, left common carotid, left subclavian; see fig. 44. Cases are reported by Huber (1777) and Walter (1785) and these are both figured by Tiedemann and Quain but there is no indication of the direction of the arch; Thomson (1863) thought them cases of right arch, Krause considered them incomprehensible from a developmental standpoint.

(c) The order of branches is: Right common carotid, left common carotid, right subclavian, left subclavian. Cases reported by Walter (1805) 2 cases, Krause (1865), Horrocks, White, Lane (1884).

(d) The order of branches is: Left common carotid, right common carotid, left subclavian, right subclavian. This is a case of low origin of the right subclavian with transposition of the carotids; only reported example is by Rau (1890).

(e) The order of branches is: Innominate, left carotid, left vertebral, left subclavian, see fig. 45. I have encountered three cases in my own dissecting rooms; in two of them the vertebral entered the fifth transverse foramen and in the other the fourth foramen. As far as the vertebral is concerned this group is similar to III, C, 1.

The following cases have been collected:

Cassebohm (Böhmer 1741), Henkel (1747), Huber (1777), Tiedemann (1822), Quain (1844), Dubrueil (1847), Barkow (1869), Carver (1869), Bradley (1871), Pye-Smith, Howse, Davies, Colley (1871), Struthers (1875), Müller (Harris 1877), Shepherd (1877), Gruber (1878), Anderson (1879), Lees (1880), Shepherd (1880), Park (1883), White, Lane, Price (1886), Hochstetter (1890) in a dog, Shepherd (1890), Thomson (1891) 5 cases, Abbott (1892), Struthers (1893) 3 cases, Freyberger (1898), Azuta (1905), Kubo & Matsui (1906), Pellegrini (1906), Waldeyer (1906), Kubo (1908), Elze (Kemmetmüller '11), Kemmetmüller (1911) 7 cases, Stein (1911), Adachi (1914) 9 cases.

(f) The order of branches is: Innominate, left carotid, left subclavian, left vertebral; see fig. 46.

This condition is much less frequent than the preceding; cases have been reported by Meckel (1816), Tiedemann (1822), Szawlowsky (1906) and Adachi (1914) 2 cases.

(g) The order of branches is: Innominate, made up of the right common carotid and the right vertebral, the left common carotid, the left subclavian and the right subclavian. These cases have been previously reported under II, *D*, 2, and need not be repeated here.

(h) The order of branches is: Innominate made up of the right common carotid, the right vertebral and the left common carotid, the left vertebral, the left subclavian and the right subclavian. Cases have been reported by Brodie (1889) and Abbott (1892).

(i) The order of branches is: Right subclavian, a common stem for the carotids, left vertebral, left subclavian. A case has been reported by Hall (1870).

(k) The order of branches is: Innominate, made up of the right common carotid and the right internal mammary, left common carotid, left subclavian, right subclavian. This condition was observed by Ludwig (1764).

(l) The order of branches is: Innominate, left carotid, left subclavian, right vertebral. For cases illustrating this condition see section II, *D*, 3.

(m) The order of branches is: Innominate, left internal carotid, left external carotid, left subclavian. The group of cases listed under II, *D*, 7 are examples of this condition.

(n) In right aortic arch the order of branches is: Left carotid, right carotid, right subclavian, left subclavian. This arrangement has already been discussed in section II, *C*, 2, and a list of reported cases given.

(o) The order of branches is: Right carotid, left carotid, left subclavian, right subclavian. This arrangement is the counterpart of the preceding and represents the simplest condition in the cases of low origin of the right subclavian.

Since the classification under II, *D*, 1 is from a different standpoint, the lists of cases, while including this condition, do not in-

dicate which are cases of four branches from the arch arranged in this order; the following list is given to satisfy such grouping.

Cassebohm (Böhmer 1741), Hoffmann (1751), Mieg (1753), Löseke (1754), Pohl (1773), Bayford (1789), Cruickshank (1789), Hulme (1789), Brewer (1791), Valentin (1791), Sandifort (1793), Monro (1797), Isenflamm (1800), Meckel (1805), Autenreith & Pfeleiderer (1806) 2 cases, Zagorsky (1810), Herold (1812), Isenflamm & Fleischmann (1815), Meckel (1816) 3 cases, Otto (1816), Kirby (1818), Colles (1820) 4 cases, Stedman (1823), Hart (1826), Cerutti (1827), Mayer (1827), Weber (1829), Hopkinson (1830), Otto (1830) 3 cases, Cruveilhier (1831), Cruveilhier & Lenoir (1832), Fleischmann (1835), Harrison (1839) 2 cases, Liston (1839), Todd (1839), Gorgone (1841), Quain (1844), Reid (1846) 2 cases, Arnold (1847), Blandin (1842), Demarquay (1848) 2 cases, Stachelroth (1850), Frandsen (1854), Oehl (1859) 2 cases, Peacock (1860) 4 cases, Turner (1862) 4 cases, Barkow (1866), Barwell (1867), Barkow (1869) 6 cases, Peacock (1870), Eppinger (1871), Mears (1871), Pye-Smith, Howse, etc. (1871), Düben (1876), Krause (1876), Shepherd (1877), Zenker (1878) 5 cases, Flesch (1879), Walsham (1880), Wiltshire (1881), Brown (1882), Giacomini (1882) 2 cases, Ozenne (1883), Hor-racks, White, Lane (1884), Beisso & Giuria (1886), Struthers (1888), Deaver (1889), Mann (1889), Dunn, Washburn & Targatt (1890), Ledouble (1890), Thompson (1890), Bothezat & Chatinière (1891), Thomson (1891) 2 cases, Faure (1895), Testut (1896) 2 cases, Miura (1897), Anile (1898), Holzapfel (1899), Rolly (1899), Hamann (1900), Ledouble (1901) 3 cases, Bouchet (1903), Gérard (1906), Pearce-Gould (1909), Geddes (1910), Hasebe (1912), Cobey (1914), Warren Museum 2 cases.

(p) The order of branches is: Innominate, internal mammary (dext.), left carotid, left subclavian. Cases reported by Loder (1781) and Meckel (1816).

(q) The order of branches is: Innominate, right inferior thyroid, left carotid, left subclavian. Two cases are reported by Meckel (1816).

(r) This is similar to the preceding except that the inferior thyroid goes to the left side and is situated between the left carotid and left subclavian. Cases are reported by Nicolai (1725), Hyrtl (1841), Gottschau (1885) 2 cases, Taylor & Grell (1902).

(s) The order of branches is: Innominate, left carotid, left superior intercostal, left subclavian. Macalester (1886) reported two examples of this condition.

(t) The order of branches is: Innominate, left thymic, left

carotid, left subclavian. Cases reported by Huber (1777) and Hyrtl (1841).

2. *Number of Branches Five*.—The number of branches from the arch five and classified according to their arrangement as follows:

(a) The order of branches is: Innominate, right vertebral, left carotid, left vertebral, left subclavian; see fig. 48. Cases are reported by Penada (1801), Fiorati (1805), Meckel (1805), Huber (Tiedemann, 1822).

(b) The order of branches is: Innominate, composed of the right carotid and vertebral, left carotid, left vertebral, left subclavian, right subclavian. These cases are included in section II, *D*, 1, and are as follows:

Tiedemann (1846) 2 cases, Bankart, Pye-Smith, Phillips (1869), Barkow (1869), Giacomini (1882), Brenner (1883), Shepherd (1890).

(c) The order of branches is: Right subclavian, right carotid, left carotid, left vertebral, left subclavian. This condition has been reported by Petsche (1736) and Loder (1781).

(d) The order of branches is: Right carotid, left carotid, left vertebral, left subclavian, right subclavian. These cases have been reported as a part of the list of section II, *D*, 1, classifying the low origin of the right subclavian.

They are as follows:

Koberwein (1810), Meckel (1820), Godman (1824), Hesselbach (1824), Quain (1844) 2 cases, Bankart, Pye-Smith, Phillips (1869), Pye-Smith, Howse, Davies, Colley (1871), McArdle (1885).

(e) The order of branches is: Right carotid, left carotid, left subclavian, left vertebral, right subclavian. This is similar to the last group, except that the left vertebral follows the left subclavian on the arch; a case has been reported by Wagner (1828).

(f) The order of branches is: Innominate, right internal mammary, left carotid, left vertebral, left subclavian. Cases have been reported by Casselbohm (Böhmer, 1741) and Meckel (1816).

(g) In a right arch the order of branches is: Left carotid, right carotid, right vertebral, right subclavian, left subclavian. Cases

are reported by Otto (1824), Hermann (1830), Barkow (1869), Watson (1877) and Abbott (1892).

(h) In a right arch the order of branches is: Innominate, composed of the left carotid and left vertebral, right carotid, right vertebral, right subclavian, left subclavian. A case has been reported by Brenner (1883).

3. *Number of Branches Six*.—The number of branches from the arch six; classified according to arrangement as follows:

(a) The order of branches is: Right subclavian, right vertebral, right carotid, left carotid, left vertebral, left subclavian; see fig. 49. Cases are reported by Müller (Meckel, 1817), Tiedemann (1822) and Harrison (Quain, 1844).

(b) The order of branches is: Innominate, left carotid, two left vertebrals, left inferior thyroid, left subclavian. A case is reported by Kemmettmüller (1911); in this case a thyreoidea ima came from the innominate.

§ VIII

E. Irregularities of the Individual Arteries Grouped Together

Irregularities of the several arteries are grouped together in this section under the headings of the arteries for the benefit of those who wish to consult anomalies from this standpoint.

1. *Thyreoidea Ima*.—The thyreoidea ima was first described by Nicolai (1725) and, as Neubauer (1722) pointed out, must not be confused with the inferior thyroids. Its frequency has been placed as high as 10 percent (Morris's *Human Anatomy*, Jackson), but this would appear to be too high; Adachi (1914) encountered only one case in 271 subjects. In my own experience two cases, one from the arch between the left carotid and left subclavian and one from the innominate, have been found.

The artery when present shows wide variation in its origin; Gruber (1872) analyzed 80 reported cases as follows: from the arch 12 cases, 9 between innominate and left carotid, 2 between right subclavian and right carotid, 1 between the left carotid and subclavian; 39 from the innominate; 16 from the carotid; 6 from the internal mammary; 3 from the right subclavian; 1 from the

right inferior thyroid; 1 from the transverse scapular. It may accompany other irregularities as in the cases of Patterson (1884) and Taylor & Grell (1902). Keith (1895) has observed the artery in the chimpanzee.

The following references are offered; and for illustration see fig. 41.

From the innominate: Neubauer (1785), Shepherd (1877) (1880), Beaumanoir (1882), Paterson (1884), Shepherd (1889), Freyberger (1898), Taylor & Grell (1902).

From the arch: Nicolai (1725), Neubauer (1772), Loder (1781), Neubauer (1785), Portal (1804), Thiloco (1804), Meckel (1816), Tiedemann (1822), Breschet (1826), Velpeau (1826), Otto (1830), Blandin (1834), Harrison (1839), Quain (1844), Gruber (1845 and 72), Hyrtl (1859), Kemmetmüller (1911), Adachi (1914).

2. *Thymic Arteries.*—These may arise from the ascending aorta, section III, *A*, 2, from the arch, section III, *D*, 1, *t*, or from the innominate, Taylor & Grell (1902). This is an infrequent anomaly and of little morphological interest.

3. *Internal Mammary.*—This may arise from the ascending aorta, section III, *A*, 2, from the aortic arch, sections III, *D*, 1, *p*, and III, *D*, 2, *f*, and from the innominate, section III, *D*, 1, *k*.

4. *Vertebrals.*—These show a wide range of variation, which has been exhaustively studied by Kemmetmüller (1911); he has shown that the foramen which the artery enters indicates which segmental is represented in its origin and this assists materially in classifying some of the anomalies. His general classification is excellent, but too exhaustive to be followed in this brief review.

The right vertebral may arise from the aortic arch between the innominate and the left carotid, section III, *D*, 2, *a*; from the arch between the right subclavian and right carotid, section III, *D*, 3, *a*; from the arch between the right carotid and right subclavian in cases of right aortic arch, section III, *D*, 2, *g* and *h*; from the innominate in cases of low origin of the right subclavian, sections II, *D*, 1, and II, *D*, 2; as the last branch from the arch, section II, *D*, 3.

The left vertebral may arise, from the aortic arch just preceding the left subclavian, sections III, *C*, 1; III, *D*, 1, *e*, *h*, *i*;

III, *D*, 2, *a*, *b*, *c*, *d*, *e*, *f*; III, *D*, 3, *a b*; from the arch as the last branch, sections III, *C*, 2, III, *D*, 1, *f*; from the innominate, section III, *D*, 2, *h*.

§ IX

IV. THE VARIATIONS IN THE DEVELOPMENT OF THE THORACIC DUCT

Anomalies of the thoracic duct are considered in this paper because they frequently appear in conjunction with the cases of low origin of the right subclavian artery. Calori (1890) has studied this condition and concludes that there is no relation between the two anomalies; with this conclusion I am agreed because an analysis of the cases of low subclavian shows that only a part of them also have an anomalous thoracic duct and that the type of irregularity is not constant and may be found in cases with no other developmental defect.

The irregularities in the position and number of connections of the left duct with the venous system are matters of common knowledge and need not be reviewed; we will confine this review to the cases in which all or a part of the system opens into the veins on the right side.

We are quite sure that the thoracic duct begins as a paired structure in relation to the two dorsal aortae and that the single duct is the result of a fusion of the two ducts in somewhat the same manner as the single dorsal aorta is formed. More observations are needed at the cephalic end to determine whether the right duct normally develops as the right aorta does and disappears by a similar atrophy. The embryonal history may be illustrated if we may consider these cases of arrested development, or rather development in the type of embryonal stages. Sömmerring (1841) saw a case in which two ducts ran from the receptaculum chyli to the venous angles in the neck, one duct opening on the right and one on the left. In Duval's (ref. Todd '39) case the duct was double in the abdomen. Butler (1903) saw a case in which the duct was double in the thorax, then single for about an inch opposite the third thoracic vertebra, then continued as two separate ducts, one opening on the left and the other on the right. Numerous examples have been reported in which both

ducts persist above, their union occurring opposite the third or fourth vertebra, see my case, page 34, illustration fig. 25, and examples below.

There is a specimen in the Warren Museum in which the duct passes up on the right of the aorta to the third dorsal vertebra where it crosses to the left, divides into two trunks and these continue as separate channels to their termination, one in the venous angle and the other in the jugular behind; both are left ducts. All the arteries are normal.

Persistence of both the right and left duct is seen in conjunction with double aortic arch, Watson (1877), and in low origin of the right subclavian, my case, page 34; it may be noted in the latter that the left duct is smaller than the right, suggesting that this is an intermediate stage in the cases of persistent right duct only.

Persistence of the right duct and obliteration of the left has been observed in cases of right aortic arch, of the type presenting a left innominate, Thomson (1863), Reid (1914), case II. It has also been observed in right aortic arch of the type in which the left subclavian is the last branch, Combes & Christopherson (1884). It may be found in cases of low right subclavian, see below, although in these double duct is almost as frequently encountered.

From the above it will be seen how difficult it is to discover a relationship between arterial variations and thoracic duct variations. It would seem that the factors which operate to produce a low right subclavian artery also tend to establish the right duct as a functioning structure. If as pointed out, page 33, the low right subclavian is related to the cases of right aortic arch of the type having a low left subclavian we would expect, reasoning as above, that the left duct would be the one developed and this is the case. This result in the case of the right arch with low left subclavian, however, does not prove that the disturbing developmental factors have influenced the duct for we are here dealing with a duct that is normal.

I would conclude from a consideration of all of the cases of anomalous thoracic duct, taken in conjunction with arterial varia-

tions, that duct irregularities are independent of arterial variations except in so far as developmental disturbances affecting the arteries may be so far reaching as also to affect the thoracic duct.

The following is a list of cases illustrating thoracic duct anomalies:

Duct opening on both sides in cases of low right subclavian: Meckel (1772), Cruickshank (1789), Fleischmann (1815), Brown (1882), Hasebe (1912).

Duct opening on right in cases of low right subclavian: Walter (1785), Sandifort (1793), Hart (1826), Todd (1839), Stachelroth (1850), Brenner (1883) 2 cases, McArdle (1885), Calori (1890), Gladstone & Wakeley (1915).

Right duct persists with or without other anomalies: Hommel (1737), Haller (1766), Mascagni (1787), Cruickshank (1789), Fleischmann (1815), Meckel (1816), Otto (1824-30), Todd (1839), Sömmering (1841), Teichmann (1861), Thomson (1863), Watson (1872), Combes & Christopher-son (1884), Davis (1886), Szalowsky (1888), Reid (1914).

§ X. GENERAL SUMMARY

From the preceding study certain impressions have been gained, which I will present as conclusions; fully appreciating, however, that in many cases much needed data was not possible to obtain and that the developmental problems are approached from only one standpoint.

There is no satisfactory evidence of a fifth aortic arch in any of the anomalies studied.

Factors disturbing the orderly development of the different portions of the vascular system may act independently of and without disturbing the normal growth processes. When the general circulatory system is seriously interfered with on account of these factors, compensation occurs either through arrest of normal atrophic processes or by enlargement of normal channels.

The factor or factors producing situs viscerum transversus seem to be operative on the aortic arch but not on the pulmonic arch.

The study of transposition shows that four separate growth

centers, viz., truncus arteriosus, bulbus cordis, ventricular limb and arterial limb, must be considered and that any one or more may show irregular development while the remainder develop normally.

It would seem that the tendency to develop is stronger in the left dorsal aorta than in the left fourth arch if we may judge from the more frequent type of right aortic arch.

Factors disturbing vascular development apparently act at a very early stage and on a very restricted area. In interpreting anomalies we should attempt to fix the time and position of disturbance if we are to throw light on the factors themselves.

There is insufficient embryological data to explain many of the anomalous arrangements of the branches from the aortic arch and it would seem that these problems might be solved by a study of the lower mammals, in which these anomalies are type forms.

There is no way of determining accurately the percentage frequency of the various anomalies in relation to the normal; the list below shows the percentage in relation to the total number of abnormalities noted. In securing these figures I have divided the irregularities into two groups one, sections I and II, relating more

Group 1

	Percent.
Irregular development of the aortico-pulmonary septum	7.3
Atresia of the pulmonary artery	6.8
Transposition of aorta and pulmonary artery	17.7
Patent ductus arteriosus	20
Double aortic arch	2.2
Right aortic arch	9
Low origin of right subclavian artery	31
Absence of the third arch	2

Group 2

One branch from aortic arch	3
Bi-innominate trunks	3
Bi-carotid trunk	25
Left carotid from the innominate	20
No innominate stem. (Low origin of subclavian not included)	8
Left vertebral from aortic arch	30
Right vertebral from aortic arch	4.7
Unusual branches from the aortic arch	2.5

particularly to arrest of development; and the other, section III, relating to fusion or separation of branches of the aortic arch. Since all of the evidence goes to show that the several disturbing developmental factors may operate independently of each other, these figures have no statistical value except to show the relative frequency of the cases included in this study.

The anomalies of the thoracic duct can all be explained from the embryological development. The duct shows less tendency to irregular development than the arteries of the same region, and the duct irregularities are independent of arterial variations except in so far as developmental disturbances affecting the arteries may be so far reaching as also to affect the thoracic duct.

§ XI. BIBLIOGRAPHY

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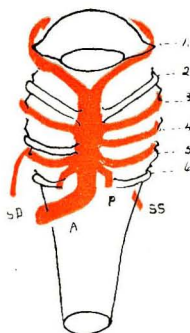
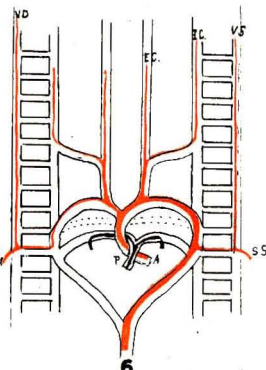
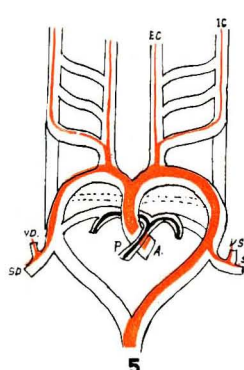
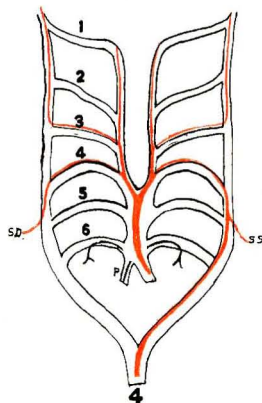
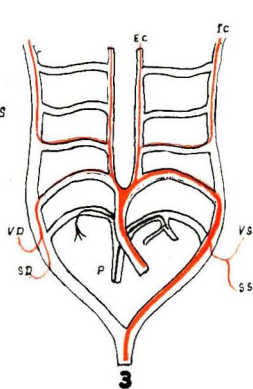
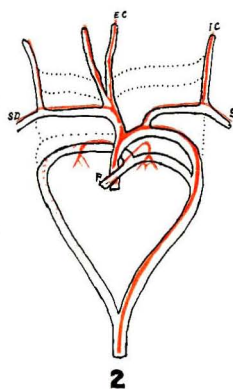
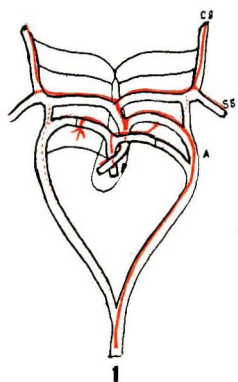
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FROM THE ANATOMICAL DEPARTMENT,
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OMAHA, NEBRASKA

ABBREVIATIONS USED IN THE FIGURES

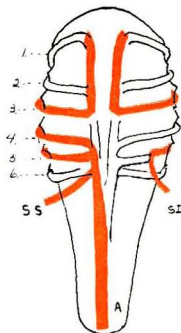
- A. Aorta.
- A D. Aorta descendens.
- C. Arteria carotis.
- C D. Arteria carotis communis dextra.
- C S. Arteria carotis communis sinistra.
- D. Ductus arteriosus (Botalli).
- E C. Arteria carotis externa.
- I C. Arteria carotis interna.
- O. Oesophagus.
- P. Arteria pulmonalis.
- S D. Arteria subclavia dextra.
- S S. Arteria subclavia sinistra.
- T. Trachea.
- T D. Ductus thoracicus.
- V D. Arteria vertebralis dextra.
- V S. Arteria vertebralis sinistra.

PLATE I.



VENTRAL.

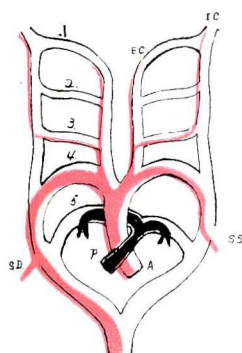
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DORSAL.

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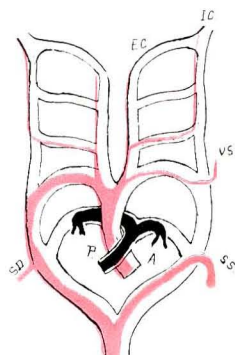
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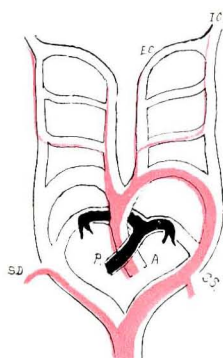
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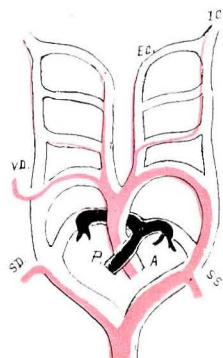
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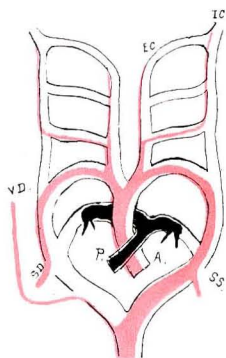
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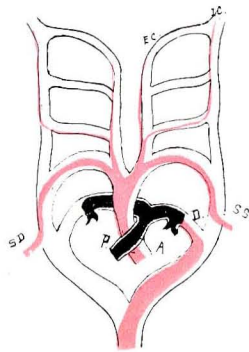
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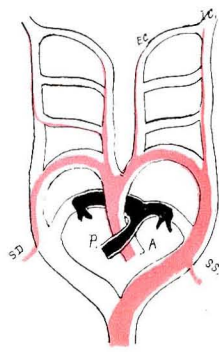
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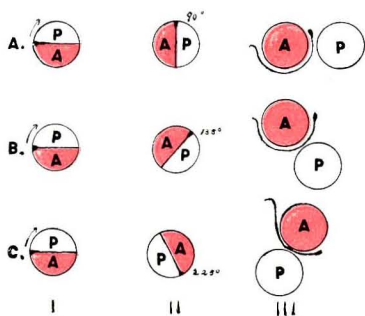
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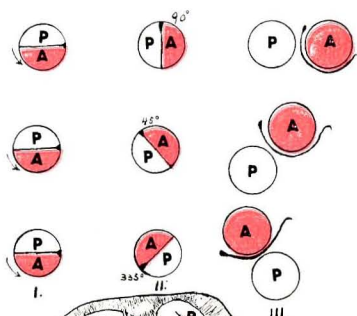
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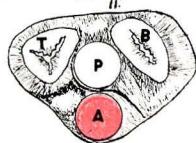
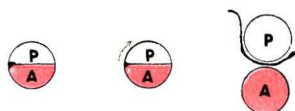
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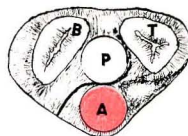
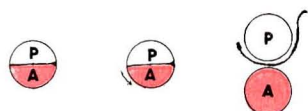
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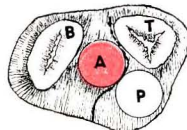
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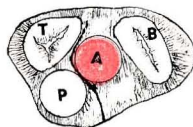
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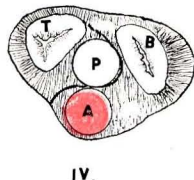
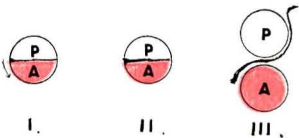


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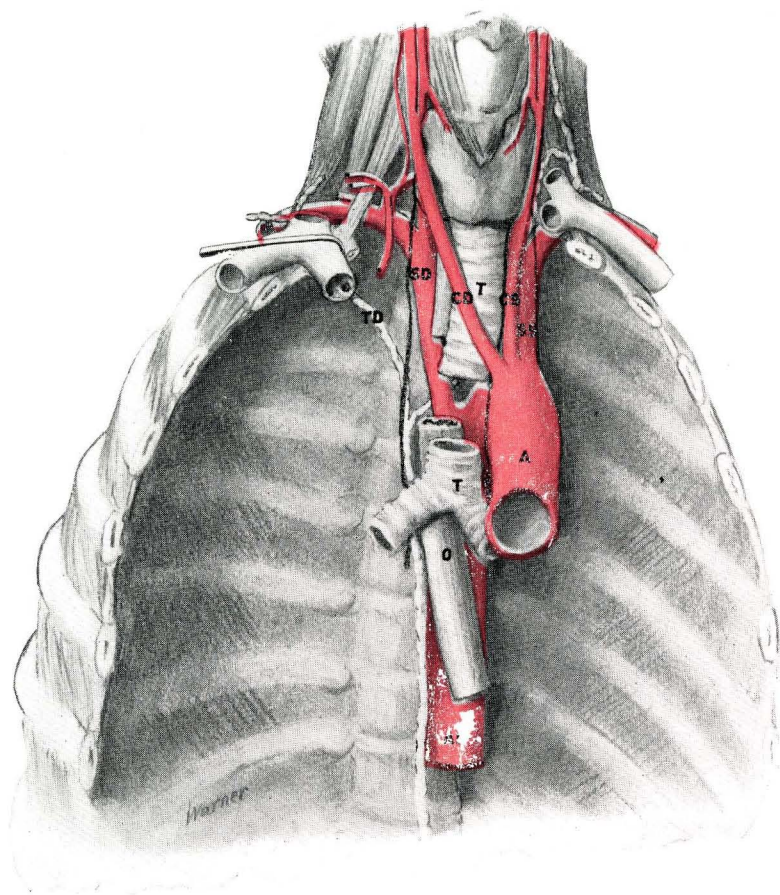
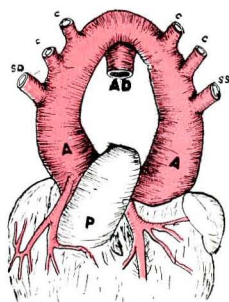
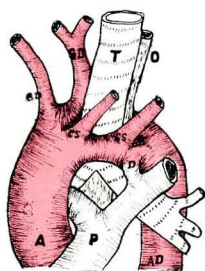


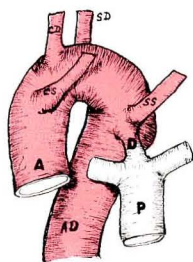
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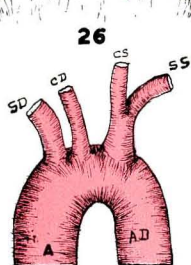
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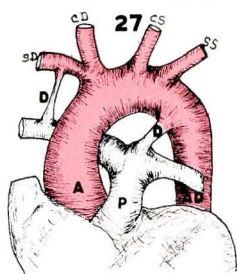
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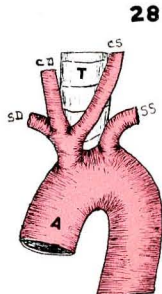
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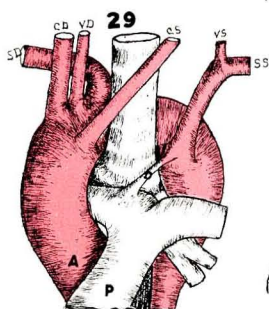
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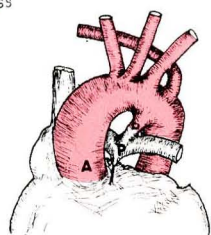
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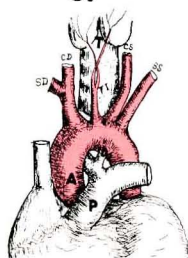
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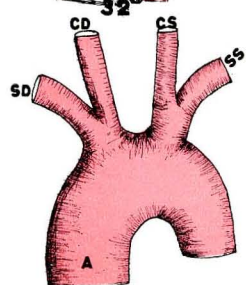
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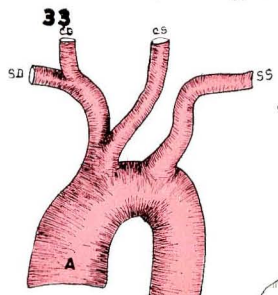
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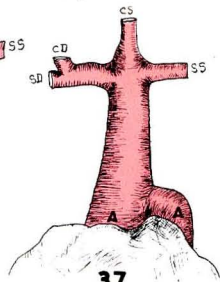
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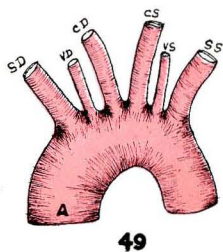
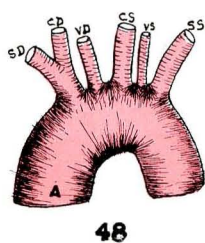
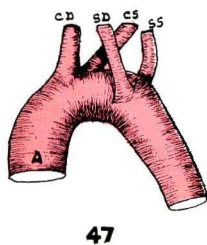
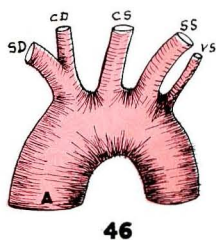
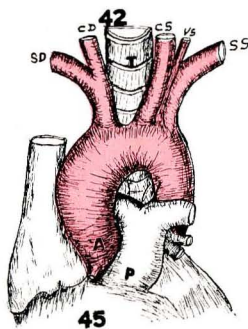
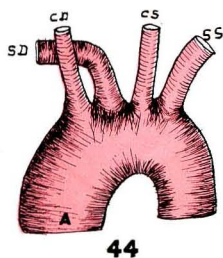
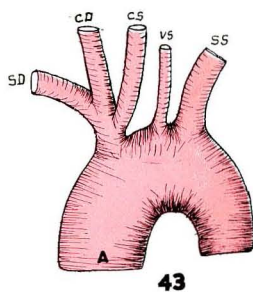
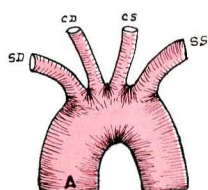
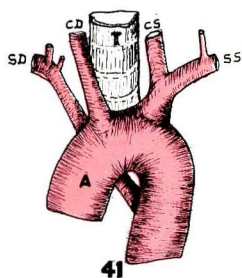
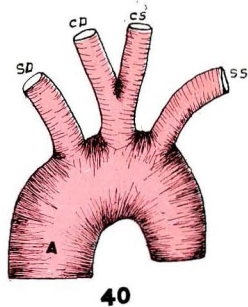
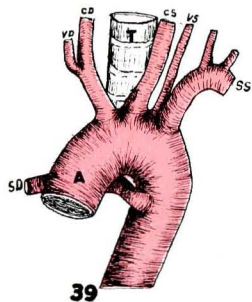
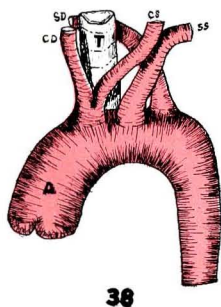


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PLATE VI.



EXPLANATION OF FIGURES

FIG. 1. This figure represents the fig. 3, Plate II, used by v. Baer to illustrate what he, at that time, thought was the type of development of the aortic arches in mammals. It was copied by Thomson (1831) as fig. 39, although he did not give v. Baer credit for the mammalian figure but for the right arch figure for birds, his fig. 30, and claimed priority for the presentation of the mammalian type.

FIG. 2. This figure represents the fig. 14, Plate IV, which v. Baer (1837) used to illustrate his embryology. He offered this figure in place of the one above to correct certain misconceptions of the fate of the aortic arches in mammals. He was of the opinion that the primitive third arch on each side forms the arterial stem which divides into the internal carotid subclavian and vertebral arteries, and that the external carotids arise from the low persisting portion of the two first arches of one half side of the head.

FIG. 3. This figure represents fig. 10, Plate VI, offered by Rathke (1857) to correct the errors in interpretation which he considered v. Baer had made for mammals. The development of the carotids and subclavians in the main is correct and the relation of the pulmonary arteries to the fifth arch is for the first time presented. This figure has frequently been presented as if it represented the first attempt at interpreting the arches, when in fact it is merely one step in the progress of our understanding of these structures.

FIG. 4. This figure represents fig. 1, Plate I, offered by Boas (1888) to illustrate the development of the aortic arches in mammals and especially to introduce an additional arch between the fourth and pulmonary arches which he believed had been overlooked by previous observers.

FIG. 5. This figure represents our present understanding of the development of the aortic arches in mammals and is used in this study as the basis for modifications explaining the various anomalies encountered in this work.

FIG. 6. This figure is adapted from Kemmetmüller (1911) to illustrate the development of the vertebral arteries and the possible variations they may assume due to anomalous development.

FIG. 7. This figure is adapted from Banchi (1907), his fig. 7, used to illustrate the method of development of the low subclavian, taking a pre-tracheal course. This method of solid reproduction of the arches was used by His, and Banchi urges that it is much easier by this type of figure to present the actual condition of the arches than by the plane figure, as above.

FIG. 8. This figure is adapted from Hochstetter's (1906) fig. 118, showing the development of the vertebral arteries; it differs in no essential detail from fig. 6, above, which was suggested by one of his earlier figures.

FIG. 9. A schematic representation of the development in cases of right aortic arch, in which there is present a left innominate; see Sect. II, C, 1.

FIG. 10. A schematic representation of the development in cases of right aortic arch in which the left subclavian artery is the last branch of the arch; see Sect. II, C, 2.

FIG. 11. This condition is similar to fig. 10, except that the left vertebral artery springs apparently from the left common carotid instead of the left subclavian; see Sect. II, C, 3. This figure was first used by Brenner (1883) as fig. 5, Plate 17.

FIG. 12. A schematic representation of the development in cases in which the right subclavian artery is the last branch from the arch. The figure was first used by Wood (1859) and has been variously modified to illustrate pre-tracheal and pre-oesophageal cases; for discussion see Sect. II, D, 1, and for illustration figs. 7, 25, 39 and 41.

FIG. 13. This is similar to fig. 12 except that the right vertebral arises from the right common carotid instead of the right subclavian artery; see Sect. II, D, 2.

FIG. 14. A schematic representation of the development in cases in which the right vertebral artery arises from the aortic arch as the last branch; see Sect. II, D, 3.

FIG. 15. A schematic representation of the development in cases in which the pulmonary artery through the ductus arteriosus gives origin to the dorsal aorta and the left subclavian artery; see Sect. II, D, 4.

FIG. 16. Like fig. 15 except that the left subclavian artery seems to arise from the ascending aorta by a common trunk with the left common carotid artery; see Sect. II, D, 5.

FIG. 17. A schematic representation of the development in cases in which the common carotid is absent and the internal and external carotids arise directly from the aortic arch; see Sect. II, D, 6 and 7.

FIG. 18. A diagram showing varying degrees of torsion of the great vessels with corresponding arrangement of the bulbar and ventricular septa: *A*, torsion of 90 degrees; *B*, normal or torsion of 135 degrees; *C*, torsion greater than normal. In both *A* and *C* we must consider the condition normal except for the actual position of the vessels and the adaptation imposed on the ventricular loop.

All of the figures on this plate are adapted from the figures of Rokitsky (1875) and Robertson (1913a); see Sect. I, C.

FIG. 19. Diagrams representing a mirror picture of fig. 18 and illustrating the possible positions of the vessels and septa in cases of situs viscerum transversus.

FIG. 20. Diagrams representing the positions of the bulbar and ventricular septa in simple transposition of the aorta and pulmonary arteries: I shows the position of the distal part of the aortico-pulmonary septum; II shows the position of the proximal aortico-pulmonary septum; III shows the possible arrangement of the great vessels in relation to the interventricular septum; IV shows the possible relation of the great vessels in relation to the ventricular chambers (heart normal and aorta opens from a tricuspid ventricle).

FIG. 21. Diagram representing the possible arrangement of vessels and heart in transposition of the great vessels accompanied by dextro-cardia.

FIG. 22. Diagram showing the possible arrangement of the ventricular chambers and the great vessels in cases in which the bulbus rotates to the left and the ventricular loop to the right.

FIG. 23. Diagram showing the possible arrangement of the ventricular chambers and the great vessels in cases of dextro-cardia, in which the vessels have developed normally.

FIG. 24. Diagram representing the possible arrangement of the ventricular chambers and the great vessels in the cases of transposition in which the aorta is in front of the pulmonary artery but opens from a bicuspid ventricle.

FIG. 25. This drawing was made from a dissection in our laboratory of a case in which the right subclavian artery arose from the beginning of the dorsal aorta and passed behind the œsophagus. The thoracic duct divided near the origin of the subclavian and opened on each side into the venous angle; see page —.

FIG. 26. This figure, representing a case of true double aortic arch, was taken from Tiedemann (1822), fig. 7, Plate IV, representing a case described by Malacarne (1788), Pt. 2, p. 119; it was copied by Quain (1844) as fig. 8, Plate V, and by Krause (1876) as fig. 108*a*.

FIG. 27. This figure, representing a case in which the arch alone is double, was taken from Tiedemann (1822), fig. 6, Plate IV, representing a case described by Hommel (1737). It is referred to in Haller Elem. Physiol., tom. 2, p. 162, and copied by Quain (1844) as fig. 7, Plate V, and by Krause (1876) as fig. 108*b*.

FIG. 28. This figure, representing a case of right aortic arch with the left subclavian artery as the last branch and the ductus arteriosus patent, was taken from Quain (1844), fig. 2, Plate VII.

FIG. 29. This figure, representing a case of right aortic arch with a left innominate trunk, was taken from Tiedemann (1822), fig. 9, Plate IV.

FIG. 30. This figure, representing a case of persistence of both the right and left ductus arteriosus, was taken from Breschet (1826), fig. 9, Plate I.

FIG. 31. This figure, representing the more or less common anomaly of left carotid artery springing from the innominate trunk, was copied from Tiedemann (1822), fig. 5, Plate II.

FIG. 32. This figure, representing a case of right aortic arch, with the left subclavian artery as the last branch and the right vertebral springing from the arch, was taken from Abbott (1892), fig. 1.

FIG. 33. This figure, representing a case of atresia of the pulmonary artery, was taken from Keith (1909), fig. 4; the pulmonary artery leaves the heart as a fibrous cord but rapidly enlarges to about normal, the ductus arteriosus is patent.

FIG. 34. This figure, representing a case of thyreoidea ima springing from the arch, was taken from Neubauer (1786), fig. 2, Plate VII.

FIG. 35. This figure, representing a case of bi-innominate trunks, was taken from Tiedemann (1822), fig. 4, Plate II, and copied by Quain (1844), fig. 9, Plate VI.

FIG. 36. This figure was drawn from a specimen of left common carotid springing from the innominate, which is in the Warren Museum.

FIG. 37. This figure, representing a single branch from the aortic arch, was taken from Tiedemann (1822), fig. 3, Plate II, illustrating the case of Klinz (1793), p. 273. It was copied by Quain (1844), fig. 6, Plate V.

FIG. 38. This figure was drawn from a specimen of low origin of the right subclavian with both carotids springing from a common stem, which is in the Warren Museum.

FIG. 39. This figure, taken from Krause (1876), fig. 115 (Macartney), Tiedemann, 1846, fig. 6, Plate XXXIX, represents a case of low origin of the right subclavian artery with the right vertebral springing from the right common carotid and the left vertebral from the aortic arch.

FIG. 40. This figure, representing a case of common trunk for the carotids, was taken from Tiedemann (1822), fig. 2, Plate III, copied by Quain (1844) as fig. 4, Plate VII.

FIG. 41. This figure, representing a case of low right subclavian artery, with a common stem for the left carotid and subclavian, was taken from Tiedemann (1822), fig. 6, Plate II; copied by Quain (1844) as fig. 8, Plate VII.

FIG. 42. This figure, representing a case in which all four branches spring separately from the arch, was taken from Tiedemann (1822), fig. 3, Plate III; copied by Quain (1844) as fig. 10, Plate VI.

FIG. 43. This figure, representing a case of the left common carotid arising from the innominate trunk and the left vertebral from the arch, was taken from Tiedemann (1822), fig. 7, Plate II.

FIG. 44. This figure, representing a case of the right subclavian arising as the second branch from the arch, was taken from Tiedemann (1822), fig. 4, Plate III; copied by Quain (1844) as fig. 11, Plate VI. The original was by Huber (1777), vol. 8, p. 75 and fig. 3.

FIG. 45. This figure is adapted from a case of left vertebral arising from the aortic arch which was found in our dissecting rooms.

FIG. 46. This figure, representing a case in which the left vertebral is the last branch from the arch, was taken from Tiedemann (1822), fig. 10, Plate III; copied by Quain as fig. 10, Plate VII.

FIG. 47. This figure, representing the right subclavian as the third branch from the arch, was reported by Walter (1785), p. 62, fig. 5, Plate III; it was copied by both Tiedemann and Quain.

FIG. 48. This figure, representing five branches from the arch, was reported by Penada (1801), p. 44, and figured by Tiedemann (1822) as fig. 4, Plate IV.

FIG. 49. This figure, representing six branches from the arch, was taken from Tiedemann (1822), fig. 5, Plate IV; copied by Quain (1844) as fig. 15, Plate VII.

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