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FORENSIC CLINICAL ANATOMY OF THE THORACIC AND ABDOMINAL AORTA

Andrea Porzionato, Veronica Macchi, Raffaele De Caro

Individual anatomy and forensic clinical anatomy

"Forensic clinical anatomy" has been defined as "the practical application of anatomical knowledge and methods (from ultrastructural to macroscopic aspects), endowed with substantial clinical/surgical implications, to the ascertainment and evaluation of medico-legal problems."[1, 2] Issues of forensic clinical anatomy acquire relevance in various fields of legal medicine (such as child abuse, sudden death, personal injury and damage), but forensic implications of clinical anatomy are particularly important in medical liability and medical malpractice.

In a survey about malpractice claims that were received by a large liability insurer covering physicians in all the US (period 1991-2005), the specialties with higher percentages of claims were neurosurgery (19.1%), thoracic-cardiovascular surgery (18.9%), and general surgery (15.3%).[3]

Issues of forensic clinical anatomy are mainly stressed in medico-legal articles about malpractice and clinical forensic medicine, although many papers about forensic pathology may also include anatomical considerations. Notwithstanding, few papers fully address the three dimensions of forensic clinical anatomy, through rigorous analysis of anatomical variability/individuality in the consideration of both clinical/surgical and forensic implications. On the other hand, in the anatomical studies and meta-analysis of the last decades, the clinical/surgical implications of variability are usually addressed but forensic implications are normally absent. Thus, the aim of the present chapter is to furtherly increase the awareness of surgeons (but even more of anatomists and forensic practitioners) about the relevance of individual anatomy in aortic surgery, with particular reference to pathophysiology and medico-legal implications of iatrogenic lesions and surgical complications.

In clinical/surgical activity (especially in the analysis of medical liability cases), the so-called "individual anatomy" acquires specific importance, being defined as the anatomy of that specific person considered in the particular moment of clinical and/or forensic relevance.[1, 2, 4, 5] Commonly, the individual anatomy does not fully correspond to the simple "textbook" anatomy, and it is better defined and expressed by anatomical variations on congenital basis, or acquired modifications due to development, aging, para-physiological conditions (*i.e.*, pregnancy, sport training, obesity), disease or surgery. Moreover, *post-mortem* transformative modifications and technical artifacts may also modify anatomy and must be considered at the moment of clinical or judicial autopsies. For instance, as it regards vascular structures, embalming procedures may produce alterations of the aortic morphology which may mimic aortic dissections both on postmortem imaging and macroscopic autopsy examination.[6]

The "individuality" of patients (in all anatomical, physiological, and pathological aspects) is also specifically recalled in the application of many clinical/surgical guidelines (which must consider the individuality of the single patient), also with reference to possible medico-legal implications. For instance, the European Society for Vascular Surgery clearly states that "the document provides a guiding principle, but the care given to an individual patient is always dependent on many factors including symptoms, comorbidities, age, level of activity, treatment setting, available techniques and other factors." In this regard, guidelines on the management of abdominal aorto-iliac artery aneurysm "under no circumstance should [...] be seen as the legal standard of care in all patients."[7] Specifically, in the medico-legal evaluation of a possible malpractice issue, we must evaluate if the surgeon specifically considered the individuality of the patient or if he/she simply apply guidelines without considering the peculiarity of the case.

The pivotal relevance of personalization in clinical practice (personalized medicine) and forensic settings (personalized justice) has been largely stressed in literature.[8, 9] The concept of "personalized medicine" was first coined by the U.S. National Cancer Institute for healthcare addressing information on individual genome, proteins and environment for diagnosis and treatment.[10] Individual anatomy is one of the prerequisites of personalized medicine, also with implications in personalized justice, considering the amount of anatomical data which are appreciable through the most modern imaging techniques (the so-called radiomics).[11]

Vascular surgery is a field with frequent anatomical congenital variability and acquired modifications, which have relevant clinical/surgical implications (increased risk of iatrogenic lesions, need for preoperative diagnostic procedures, anatomy-based surgical complications, etc.), with potential medico-legal implications. Thus, in the present chapter, we will consider how individual anatomy may impact on the aortic surgery from surgical and medico-legal points of views.

Thoracic aorta

Course and diameter

Anatomical variations or anomalies of the aorta are quite frequent and may have relevant surgical implications. Aortic contraction is a congenital constriction of the aortic lumen at the junction between the aortic arch and the descending aorta; it may be preductal (also known as infantile type) or postductal (adult type).[12] Aortic coarctation usually develops collateral pathways through intercostal, internal thoracic, thoracoacromial and vertebral arteries. Conversely, aortic pseudocoarctation is another congenital variation characterized by kinking of a tortuous aortic arch at the level of the ligamentum arteriosus; in this case, due to absence of a significant pressure gradient, collateral pathways are absent. Ductus diverticulum is a focal dilatation on the anteroinferior surface of the isthmic region of the aortic arch.[13] It is usually considered a remnant of the closed ductus arteriosus, although it has also been suggested to be a remnant of the right dorsal aortic root.[14] From the perspective of forensic clinical anatomy, it is important to recall that a prominent ductus diverticulum may be misdiagnosed as traumatic pseudoaneurysm, although smooth margins and slight convexity help in the differential diagnosis.

Regarding the variability of the course of the thoracic aorta, we may recall the cervical aortic arch, given by an elongated aortic arch running upward above the sternum (on the right) which continues in a retroesophageal descending aorta (on the left); it is frequently associated with an aberrant subclavian artery arising from the descending aorta.[12] The cervical aortic arch may cause dysphagia or respiratory symptoms and it shows higher frequency in DiGeorge and Turner syndromes.[15, 16]

Apart from the above anatomic variations or anomalies, individual dimensional characteristics of the aorta are to be specifically considered in various therapeutic approaches, such as stent-graft management.[17] For instance, "one of the anatomic requirements" is a landing zone of at least 15 mm to 20 mm proximal to the primary tear; the ideal landing zone should also be uniform in shape. Moreover, it is pivotal to select the correct device in terms of dimension, through measurement of the aortic diameter, which, however, is generally crescentric or elliptical in shape and only a fraction of the normal transaortic diameter. Thus, the diameter of the non-dissected aorta immediately proximal to the entry tear is mainly considered. If the entry tear is located immediately distal to the left subclavian artery, the diameter at the level of the short segment between left common carotid and left subclavian artery is measured. These diameters may be considered quite a good estimate of the original size of the aorta before dissection. The measurement is usually oversized by about 10% to select the correct stent-graft diameter to achieve secure anchoring and tight circumferential seal.[17] Incorrect evaluation of the individual anatomy may be at the basis of stent-graft collapse, and it will have to be specifically analyzed in medico-legal evaluation of a possible medical malpractice hypothesis. Stent-graft collapses have been attributed in some series to oversizing of the stent graft to the aorta.[18, 19] Some authors ascribed this type of complication to the difficulty of sizing stent grafts in the case of extremely small true lumen; moreover, the occurrence of these complications may also be due to the tendency of some experienced surgeons to push the anatomic limits of stent-graft approach for aortic dissections (for which no ideal commercially available devices exist).[17]

Aortic arch branching

From the convexity of the aortic arch the brachiocephalic trunk, left common carotid artery and left subclavian artery usually arise in sequence. The prevalence of this pattern has been reported in 65-95% in White and Japanese individuals[12, 20-29] and about 50% in Black subjects.[22-23]

The second most frequent pattern (11-27%, also called "bovine arch")[24, 27-29] presents a common trunk for right subclavian, right common carotid and left common carotid arteries, and a second branch given by the left subclavian artery. The prevalence of this pattern is higher in Black subjects.

The third most frequent pattern (0.79-8%)[12, 24-30] involves the origin of the left vertebral artery directly from the aortic arch, between the common carotid artery and the left subclavian artery. When the left vertebral artery directly arises from the aortic arch, it usually enters the fifth or fourth transverse foramen instead of the sixth one.[31] This pattern shows a higher risk of iatrogenic damage, with hemorrhage and permanent neurologic deficit, in the case of wide lateral decompression in anterior surgery of the cervical spine.[32]

Other anatomical variations (usually rarer than 1%) include the following: 1) common origin of the two common carotid arteries from a common trunk; 2) the presence of a (lusoria) right subclavian artery originating from the aortic arch distally with respect to the left subclavian artery (in these cases the right subclavian artery may pass behind the esophagus, between the esophagus and the trachea, or anteriorly to the trachea); 3) the presence of a common trunk for the two common carotid arteries and of another common trunk for the two subclavian arteries; 4) the independent origins of the right subclavian and common carotid arteries (arch with four branches); and 5) the presence of a thyroid ima artery.

From a clinical point of view, the lusoria right subclavian artery and the common bi-carotid trunk may produce compression of the esophagus (disphagia) and trachea (dyspnea). The thyroid ima artery may also give rise to iatrogenic hemorrhage if not recognized in anterior neck surgery.

Moreover, variant aortic arch branching has been associated with aortic dissections with entries in the aortic arch. In a series of 157 patients with acute type A aortic dissection, the rate of arch entries was significantly higher in patients with common trunk for right subclavian artery and common carotid arteries compared to patients with normal pattern. This arch pattern was also associated with higher rate of postoperative neurological injury.[33] In another study, patients with non-A non-B dissection presented with a common origin of the brachiocephalic trunk and left common carotid artery in 28% of cases and an arch origin of the left vertebral artery in 16%.[34]

Collateral branches

The origin and course of the bronchial arteries are highly variable, and this variability may have implications in thoracoscopic surgery and management of pulmonary haemorrhages.[35-37]

Cauldwell *et al.*[38] classically classified the origins of the bronchial arteries into four patterns:

- two bronchial arteries on the left and one on the right, arising as a common trunk with the right intercostal artery (40.6% of cases);
- one on the left and one on the right as common trunk with homolateral intercostal artery (21%);
- two on the left and two on the right, one of which as a common trunk (20%);
- one on the left and two on the right, one of which as common trunk (9.7%).

Bronchial arteries are usually more numerous in men than women.[37, 39-42]

The normal origin of the bronchial arteries from the aorta goes from the upper limit of the fifth thoracic vertebral body to the lower limit of the sixth thoracic vertebral body; other origins are considered ectopic, *i.e.*, higher or lower aortic origin and arising from other arteries (internal thoracic artery, thyrocervical trunk, subclavian artery, costocervical trunk, brachiocephalic artery, coronary artery, pericardiophrenic artery, inferior phrenic artery).[12]

The thoracic esophagus is irrorated from branches arising directly from the aorta, or from the bronchial arteries and the right intercostal arteries. In the abdomen, it usually receives branches from the left gastric artery and from the left inferior phrenic artery.

The superior phrenic arteries can originate, usually in the number of two, directly from the thoracic aorta or from the tenth intercostal artery.

Complications of aortic stent-graft may be due to occlusion of collateral arteries; their prevention requires specific consideration of the individual anatomy. For instance, it has been stressed that long stent grafts provide a more normal anatomic configuration and may increase the rate of false-lumen thrombosis. However, extension of stent grafts into the distal third of thoracic aorta may increase the risk of spinal cord ischemia and paraplegia due to occlusion of intercostal arteries.[17] In this sense, extensive coverage of intercostal arteries is discouraged due to increased risk of spinal cord ischemia and bare stents have been advocated for the distal thoracic aorta.[43] The spinal cord is irrorated by many different segmental arteries, among which the great anterior radicular artery of Adamkiewicz, which (although highly variable) usually arises from the left posterior intercostal artery at T9-L1 levels.[12] The Recommendations for the Treatment of Thoracic Aortic Pathologies by the European Association for Cardio-Thoracic Surgery and the European Society for Vascular Surgery[44] state that "as imaging is still not able to provide us with a detailed description of intraspinal collateralization, which might be the answer to who is at increased risk for spinal cord injury, risk prediction models remain approximations, *e.g.* the collateral network concept and, developed on that basis, the 4-territory concept."[45, 46] According to the collateral network theory, there are four independent vascular territories supplying the spinal cord, *i.e.*, the left subclavian, intercostal, lumbar, and the hypogastric arteries. On the basis of a prospective 63-patient single-center cohort, Czerny *et al.*[46] concluded that "extensive coverage of intercostal arteries alone by a thoracic stent-graft is not associated with symptomatic spinal cord injury; however, simultaneous closure of at least 2 vascular territories supplying the spinal cord is highly relevant, especially in combination with prolonged intraoperative hypotension."

Abdominal aorta

Course and diameter

The abdominal aorta usually shows quite a straight course but, in some cases, a tortuous course may be present.[47, 48] In a series of 50 cases, left and right deviations have been described in 16% and 6% of cases, respectively; in one case an S-shaped curvature was found.[12]

In guidelines for the management of abdominal aortic aneurysm, many recommendations are strictly anatomical in nature. For instance, the "Society for Vascular Surgery practice guidelines on the care of patients with an abdominal aortic aneurysm"[49] state that "if it is anatomically feasible, we recommend endovascular aneurysm repair (EVAR) over open repair for treatment of a ruptured abdominal aortic aneurysm (AAA)" (level of recommendation 1 – strong; quality of evidence C – low). And regarding indications of open surgical repair (OSR): "OSR of an AAA continues to be used for patients who do not meet the anatomic requirements for endovascular repair, including short or angulated landing zones, excessive thrombus, multiple large accessory renal arteries, and small and tortuous access vessels with concomitant occlusive disease. However, fenestrated, branched, and chimney or snorkel grafts have expanded the range of complex aortic anatomy potentially treatable by EVAR." As it regards the anatomy of the neck, the above-mentioned guidelines stress that "a type-IA endoleak most often occurs in the presence of a short or severely angulated neck or a reverse tapered neck […]." A hostile neck anatomy and progressive aortic dilation and elongation also predispose to stent graft migration.[49]

Gender and ethnic related factors also contribute to the definition of the individual anatomy. A simple anatomical factor as aortic diameter is also related to gender and ethnicity and its measurement has important surgical implications. It has been stressed that lower threshold for aortic diameter in diagnosis of abdominal aneurysm might be more appropriate in women and some Asian populations.[7, 50, 51] In previous guidelines for surgery of the abdominal aortic aneurysm there were not different indications based on gender or ethnicity. However, some authors have stressed that "women experience relatively larger growths in diameter by the time of 5.5 cm because women have smaller aortas."[52] In fact, the risk for elective EVAR with an intervention threshold of 5.2 cm for women has been reported to be comparable in women to a threshold of 5.5 cm in men.[53] Thus, the latest practice guidelines from Society for Vascular Surgery[49] and European Society for Vascular Surgery[7] had decreased the intervention threshold of women to 5.0 cm.

Further considerations are present in guidelines regarding imaging methodology to measure aortic diameter. For instance, inner to inner wall measurements are about 0.3-0.6 cm smaller than outer to outer wall measurements.[54-56] Thus, the site and plane of measurement of aortic diameter should be specified.[7]

Collateral branches

Therapeutic approaches to abdominal aneurysm must take into account the specific distribution of collateral branches, which are highly variable, for potential consequences of their occlusion.

Complications of different approaches to abdominal aortic aneurysm (colon ischemia, buttock claudication, sexual dysfunction) are anatomically related to the occlusion extent of aortic collateral branches. In fact, perfusion of colon, rectum and pelvis is given by a complex collateral network connecting superior mesenteric artery, inferior mesenteric artery, internal iliac arteries, and collaterals from the circumflex iliac and common and deep femoral arteries. The anatomo-functional characteristics of this collateral network are highly variable and may be furtherly modified by aging, disease, and previous surgery, so that specific evaluation of the individual anatomy is included in guidelines and must be considered by surgeons in programming the specific therapeutic approach for each case. For instance, guidelines of the Society for Vascular Surgery "recommend reimplantation of a patent IMA under circumstances that suggest an increased risk of colonic ischemia."[49] It is furtherly specified in the text of the guidelines that selective reimplantation may be considered in the presence of interruption of the marginal artery due to prior colectomy, in advanced age, in patients with underlying celiac and superior mesenteric artery occlusive disease, particularly in the presence of a large meandering artery. The guidelines of the European Society for Vascular Surgery also state that "there is no evidence in the literature to support reimplantation of a patent inferior mesenteric artery, but it may be considered occasionally in selected cases of suspected insufficient visceral perfusion with risk of colonic ischemia, for example if the superior mesenteric artery is occluded and the IMA is an important collateral."[7]

Preservation of at least one internal iliac artery is also recommended both by the Society for Vascular Surgery[49] and European Society for Vascular Surgery.[7]

Accessory renal arteries have been reported in percentages going from 9% to 20% of patients with abdominal aneurysm.[57, 58] Their occlusion usually produces renal infarction, which is well tolerated in most patients, without significant impact on long-term glomerular filtration rate, but which may increase the risk of deterioration of renal function in presence of pre-existing renal insufficiency. Occlusion of accessory renal arteries also increase the risk of type-II endoleak. Thus, the decision to accept the risk of occlusion of accessory renal arteries must be taken mainly based on individual anatomy. Both guidelines of the European Society for Vascular Surgery[7] and the Society for Vascular Surgery[49] recommend preservation of accessory renal arteries 3 mm or larger in diameter or of accessory renal arteries which supply more than one third of the renal parenchyma.

Apart from anatomy of aorta and its collaterals, also the individual anatomy of the non-vascular structures is important for the choice of the best therapeutic approach to aortic pathology. For instance, open surgery repair of an abdominal aortic aneurism may be performed using either a transperitoneal or left flank retroperitoneal approach; the indications are mainly based on patient's anatomy, also determined by disease/surgery-related modifications. In particular, an indication for retroperitoneal approach is the presence of a so-called "hostile" abdomen, due to acquired anatomical modifications, such as prior intra-abdominal interventions, irradiation, incisional hernia, or stoma, together with aneurysm associated with a horseshoe kidney (recommendation of the Society for Vascular Surgery).[49]

Forensic clinical anatomy and analysis of medical liability hypotheses

Based on the aforementioned considerations, individual anatomy must also be critically considered alongside the ascertainment and evaluation phases of medico-legal analyses related to medical malpractice hypotheses:

- relevant aspects of individual anatomy (anatomical variations or modifications) must be specifically ascertained through anatomical methodology (*i.e.*, *in vivo* and/or *post-mortem* and/or postautopsy imaging; anatomic dissections in course of judicial autopsies);
- data about individual anatomy (once fully ascertained and consistently discussed on the light of pertinent scientific knowledge and guidelines) may help in the correct application of the criteria of evaluation and in final judgment about identification of profiles of medical responsibility/liability.

In analysis of malpractice hypotheses in aortic surgery, ascertainment methods include revision of *in-vivo* imaging (possibly angiographies when present), *post-mortem* angiographies (preliminary to judicial autopsy) and eventually post autopsy imaging analyses on large *en bloc* samples including the vascular bed to be studied (for instance, angiographies of single organs or visceral regions).

The main evaluation criteria to be considered are:

- reconstruction of the physio-pathological pathway;
- identification-evaluation of errors (analysis of medical conduit);
- discussion of causal value;
- damage estimation.[59]

The individual anatomy may acquire specific relevance in each of the above criteria. From the perspective of forensic clinical anatomy, in the analysis of the medical conduit it is pivotal to verify if surgeons identified relevant anatomical data and how they considered anatomy in the context of diagnostic, prognostic and therapeutic procedures.[5] Iatrogenic lesions or surgical complications may derive from omitted identification or insufficient consideration of relevant anatomical data (*e.g.*, lesion of an unidentified variant/modified artery or ischemic consequences due to occlusion of an artery in the absence of an adequate collateral network).

The identification of an "anatomy-related" error implies a following discussion about its causal value, based on anatomo-physio-pathological pathway, possibly expressed in probability level (exclusion, possibility, probability, certainty). In summary, the medico-legal evaluation of causality should verify if the damage (even anatomically defined) would have been prevented (and with which probability) in presence of correct identification/management of individual anatomy (counterfactual reasoning).[5]

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