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Review Article

Anatomical Variations in the Branching Pattern of the Abdominal Aorta: A Comprehensive Review with Clinical Implications

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Abstract

The abdominal aorta is the principal arterial conduit supplying the abdominal viscera, retroperitoneal organs, abdominal wall, and lower extremities. Although the classical branching pattern described in standard anatomical textbooks is commonly encountered, numerous variations have been documented in cadaveric, angiographic, and radiological studies. These variations arise during embryological development due to persistence, regression, or anomalous fusion of primitive ventral and lateral splanchnic arteries. Anatomical variations may involve the celiac trunk, superior mesenteric artery, inferior mesenteric artery, renal arteries, gonadal arteries, lumbar arteries, and terminal bifurcation of the aorta. Recognition of these variations has become increasingly important in modern clinical practice because of the widespread use of endovascular procedures, organ transplantation, laparoscopic surgeries, oncological resections, and interventional radiology techniques. Failure to identify anomalous vessels can result in inadvertent vascular injury, ischemic complications, hemorrhage, and unsuccessful surgical outcomes. Advances in multidetector computed tomography angiography and magnetic resonance angiography have substantially improved the detection and characterization of vascular variants before intervention. This review summarizes the embryological basis, prevalence, classification, and clinical significance of major abdominal aortic branching variations reported in the literature. Understanding these anatomical patterns is essential for anatomists, radiologists, vascular surgeons, transplant surgeons, urologists, and gastroenterologists to facilitate safe surgical planning and improve patient outcomes.

Keywords: Abdominal aorta; Anatomical variation; Celiac trunk; Renal artery; Vascular anatomy.

INTRODUCTION

The abdominal aorta represents the continuation of the thoracic aorta after passing through the aortic hiatus of the diaphragm at the level of T12 vertebra. It descends anterior to the vertebral column and terminates at the level of L4 by dividing into the common iliac arteries. Along its course, it gives rise to several paired and unpaired branches that supply abdominal viscera, kidneys, gonads, diaphragm, abdominal wall, and lower limbs [1].

The classical description of abdominal aortic branching includes three unpaired ventral branches the celiac trunk, superior mesenteric artery (SMA), and inferior mesenteric artery (IMA) along with paired branches such as inferior phrenic, middle suprarenal, renal, gonadal, and lumbar arteries [2]. However, developmental alterations occurring during embryogenesis frequently result in considerable anatomical variability. Such variations may affect the origin, number, course, caliber, and branching pattern of abdominal arteries [3].

Knowledge of vascular anatomy has gained significant clinical relevance with the advent of minimally invasive surgical techniques and advanced imaging modalities. Endovascular aneurysm repair, renal transplantation, hepatobiliary surgery, pancreatic resections, adrenalectomy, nephrectomy, and interventional radiology procedures require precise understanding of arterial anatomy before intervention [4]. Unexpected vascular anomalies may increase operative time, blood loss, postoperative complications, and mortality.

Among all abdominal aortic branches, variations of the celiac trunk and renal arteries have received particular attention because of their high prevalence and surgical importance. Studies have reported accessory renal arteries in 20–30% of individuals, while variations of the celiac trunk occur in approximately 10–50% depending on the classification system used [5,6]. Similarly, anomalies involving common trunks shared by the celiac and mesenteric arteries may have profound implications during gastrointestinal surgeries and liver transplantation [7].

Recent advances in multidetector computed tomography (MDCT), digital subtraction angiography, and magnetic resonance angiography have enabled accurate identification of vascular variants in living individuals [8]. Consequently, a detailed understanding of these patterns has become indispensable not only for anatomists but also for clinicians involved in diagnostic and therapeutic procedures.

This review aims to provide a comprehensive overview of the anatomical variations in the branching pattern of the abdominal aorta, discuss their embryological basis, summarize major classification systems, and highlight their clinical implications in contemporary medical practice.

Embryological Basis of Abdominal Aortic Variations

Understanding abdominal arterial variations requires an appreciation of embryological vascular development. During early embryogenesis, paired dorsal aortae give rise to multiple ventral, lateral, and dorsal segmental branches supplying developing organs [9].

The ventral splanchnic arteries initially form a series of paired vessels supplying the primitive gut tube. Longitudinal anastomoses subsequently develop between these vessels. Selective regression and persistence of these channels result in the formation of the celiac trunk, superior mesenteric artery, and inferior mesenteric artery. Any alteration in this process can lead to anomalous origins or common trunks involving these vessels [10].

The kidneys initially develop in the pelvic region and ascend to their final lumbar position during fetal development. Throughout this ascent, they receive blood supply from successively higher arterial branches originating from the aorta. Normally, inferior vessels regress while superior vessels persist. Failure of regression results in accessory or multiple renal arteries, one of the most common vascular variations encountered in clinical practice [11].

Similarly, gonadal arteries originate from the lateral mesonephric branches of the aorta. Variations in their origin may occur due to persistence of embryonic vascular channels. Aberrant gonadal arteries may arise from renal, suprarenal, lumbar, or accessory renal arteries [12].

The inferior phrenic and suprarenal arteries also exhibit developmental variability owing to complex embryological interactions among neighboring vascular networks. These variations are frequently observed during retroperitoneal surgeries and radiological interventions [13].

Embryological mechanisms therefore provide the foundation for understanding the wide spectrum of abdominal arterial variants encountered in anatomical and clinical studies.

Variations of the Celiac Trunk and Mesenteric Arteries

The celiac trunk is typically the first unpaired ventral branch of the abdominal aorta and classically trifurcates into the left gastric, common hepatic, and splenic arteries, a configuration described by Haller as the "Tripus Halleri" [14].

Numerous variations have been documented. One of the most widely used classifications was proposed by Michels and later modified by Hiatt. These classifications describe variations involving hepatic arterial anatomy and branching patterns associated with the celiac trunk [15].

Common variations include bifurcation of the celiac trunk into hepatosplenic or gastrosplenic trunks, absence of the celiac trunk, and separate origins of its constituent branches directly from the abdominal aorta [16]. In rare instances, the celiac trunk and superior mesenteric artery arise from a common celiomesenteric trunk. The reported prevalence of this anomaly ranges between 0.25% and 2.7% [17].

The superior mesenteric artery may also demonstrate variations involving the origin of hepatic arteries, middle colic artery, or right colic artery. Replaced right hepatic arteries frequently arise from the SMA and are of major significance during pancreaticoduodenectomy and liver transplantation [18].

Variations involving the inferior mesenteric artery are less common but may include anomalous origins, altered branching patterns, or collateral communications with the superior mesenteric artery. These variations become particularly important during colorectal surgeries and management of mesenteric ischemia [19].

The presence of unusual mesenteric arterial anatomy may alter collateral circulation and influence the severity of ischemic events. Consequently, preoperative vascular mapping has become standard practice in many abdominal surgical procedures [20].

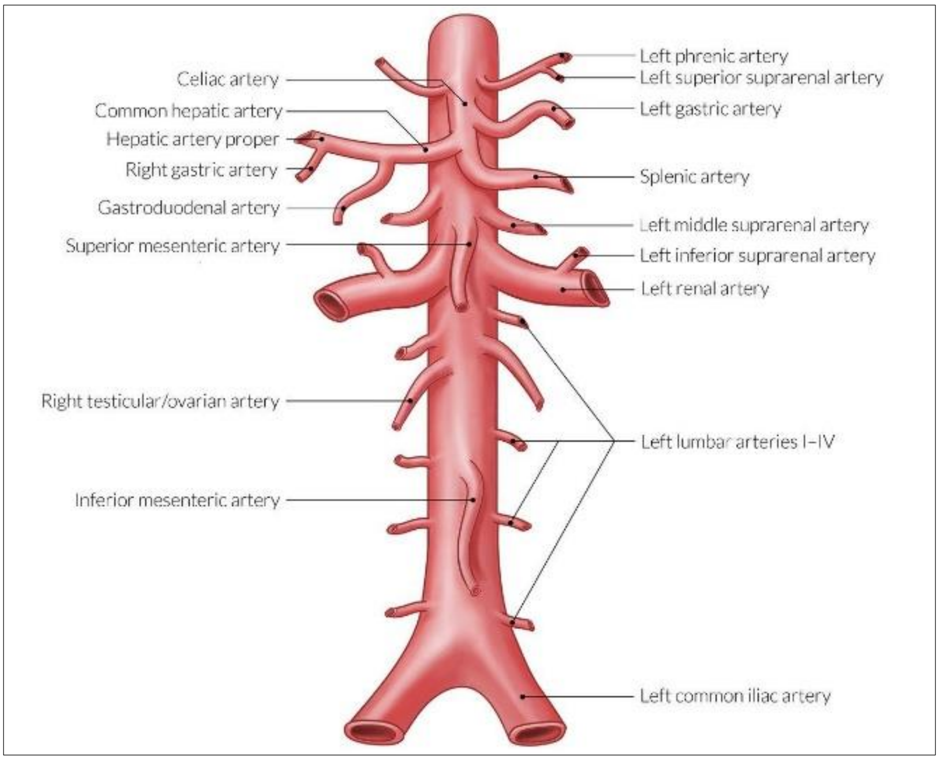

Figure 1: Classical branching pattern of the abdominal aorta showing the celiac trunk, superior mesenteric artery, renal arteries, gonadal arteries, inferior mesenteric artery, and terminal bifurcation

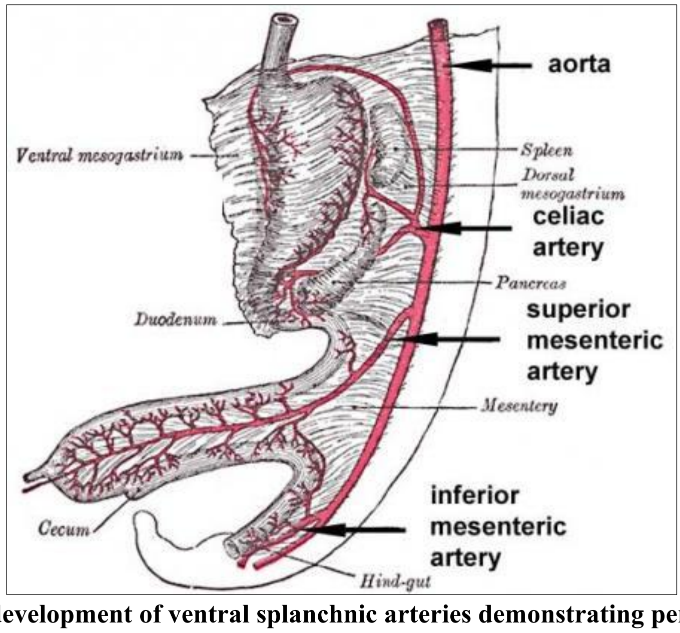

Figure 2: Embryological development of ventral splanchnic arteries demonstrating persistence and regression of primitive vascular channels leading to formation of the celiac trunk, superior mesenteric artery, and inferior mesenteric artery

Variations of Renal, Gonadal, and Other Paired Branches

Among all branches of the abdominal aorta, renal arteries exhibit the highest frequency of anatomical variation. Classical anatomy describes a single renal artery supplying each kidney; however, multiple studies have demonstrated that accessory renal arteries are present in approximately 20–35% of individuals [11].

Accessory renal arteries may enter the renal hilum alongside the main renal artery (hilar arteries) or penetrate directly into the superior or inferior poles of the kidney (polar arteries). These vessels are considered end arteries and therefore must be preserved during surgical procedures to prevent segmental renal ischemia [11,12].

Various classifications of renal arterial anatomy have been proposed. Merklin and Michels categorized renal arterial variations into accessory hilar arteries, polar arteries, and early branching patterns. Early division of the renal artery before reaching the hilum is particularly important during laparoscopic donor nephrectomy because it may complicate vascular anastomosis during transplantation [13].

Accessory renal arteries have significant clinical implications in renovascular hypertension, ureteropelvic junction obstruction, and renal transplantation. Inferior polar arteries may cross anterior to the ureter and produce extrinsic compression, resulting in hydronephrosis and impaired urinary drainage [14].

Variations involving the gonadal arteries are also frequently reported. Normally, testicular and ovarian arteries arise from the anterolateral aspect of the abdominal aorta inferior to the renal arteries. However, anomalous origins from renal arteries, accessory renal arteries, suprarenal arteries, lumbar arteries, or common trunks have been documented [15].

Knowledge of gonadal arterial variations is particularly important during renal transplantation, varicocele surgery, orchidopexy, nephrectomy, and retroperitoneal lymph node dissection. Unrecognized anomalous vessels may lead to gonadal ischemia and impaired reproductive function [16].

The middle suprarenal arteries also demonstrate considerable variability in their number, origin, and course. They may arise directly from the aorta, renal arteries, inferior phrenic arteries, gonadal arteries, or accessory renal arteries. Such variations become clinically relevant during adrenalectomy and embolization procedures performed for adrenal tumors [17].

Lumbar arteries generally arise as four paired branches from the posterior aspect of the abdominal aorta. Variations in their number and origin are frequently encountered. These arteries may contribute significantly to collateral circulation in patients with aortic occlusive disease and during endovascular aneurysm repair [18].

The inferior phrenic arteries commonly originate independently from the abdominal aorta but may also arise from the celiac trunk, renal artery, left gastric artery, hepatic artery, or common trunks. These vessels are increasingly recognized because they frequently serve as collateral feeders to hepatocellular carcinoma and are often targeted during transarterial embolization procedures [19].

Terminal branching variations of the abdominal aorta have also been described. High or low bifurcation of the aorta, trifurcation patterns, and anomalous origins of common iliac arteries may influence vascular surgical procedures, pelvic operations, and endovascular interventions [20].

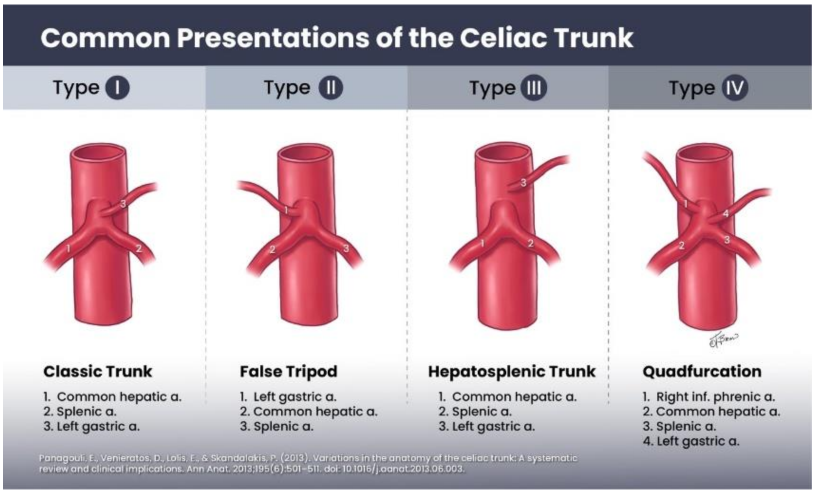

Figure 3: Common anatomical variations of the celiac trunk including hepatosplenic trunk, gastrosplenic trunk, absent celiac trunk, and celiomesenteric trunk

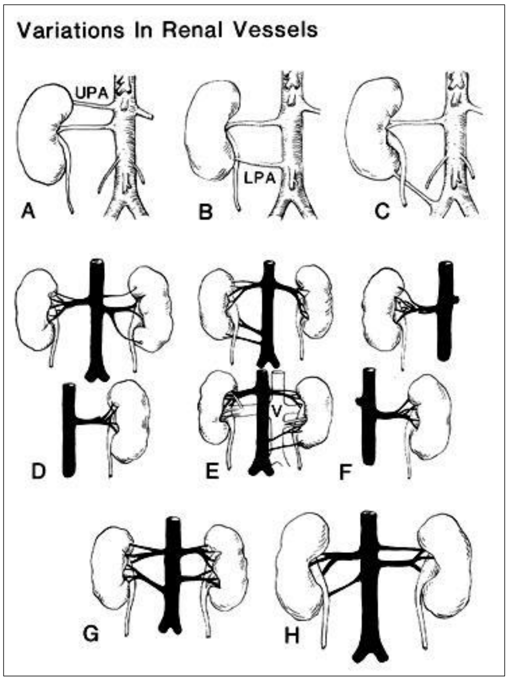

Figure 4: Accessory and multiple renal arteries supplying the kidney. Such variations are important during renal transplantation, nephrectomy, and endovascular interventions

Clinical and Surgical Implications

The clinical importance of abdominal aortic branching variations has increased dramatically with the advancement of modern surgical and interventional techniques. Detailed knowledge of vascular anatomy is now regarded as an essential prerequisite for safe operative planning and execution [1].

In hepatobiliary surgery, variations involving the celiac trunk and hepatic arteries may significantly affect liver transplantation, hepatic resections, cholecystectomy, and pancreatic surgery. Failure to identify replaced or accessory hepatic arteries can result in hepatic ischemia, biliary complications, or graft failure following transplantation [2].

Pancreaticoduodenectomy remains one of the most technically demanding abdominal procedures. Variations such as a replaced right hepatic artery arising from the superior mesenteric artery may traverse the pancreatic head and are particularly susceptible to inadvertent injury during dissection [3].

Renal transplantation represents another field in which vascular anatomy is of paramount importance. The presence of multiple renal arteries was once considered a contraindication to transplantation; however, advances in microsurgical techniques now permit successful transplantation in such cases. Nevertheless, accessory arteries increase operative complexity and may contribute to vascular thrombosis, urinary leakage, or graft dysfunction if not adequately managed [4].

In urological surgery, accessory lower polar arteries may cause ureteropelvic junction obstruction and hydronephrosis. Recognition of these vessels on preoperative imaging allows surgeons to select appropriate reconstructive techniques while preserving renal perfusion [5].

Endovascular aneurysm repair (EVAR) has become a preferred treatment modality for abdominal aortic aneurysms. Successful deployment of endografts requires precise evaluation of branch vessel anatomy, particularly the renal and mesenteric arteries. Aberrant vessels may influence device selection and procedural planning [6].

Interventional radiologists frequently encounter abdominal arterial variations during angiography, embolization, and vascular stenting procedures. Identification of variant anatomy reduces procedural complications and improves technical success rates [7].

The increasing use of minimally invasive laparoscopic and robotic surgeries has further highlighted the need for accurate preoperative vascular mapping. Unexpected arterial variants can lead to uncontrolled hemorrhage, prolonged operative time, conversion to open surgery, and increased postoperative morbidity [8].

Multidetector computed tomography angiography has emerged as the gold standard for preoperative vascular assessment. Three-dimensional reconstruction techniques provide detailed visualization of arterial anatomy and enable comprehensive surgical planning [9].

From an educational perspective, awareness of abdominal arterial variations is essential for anatomists, surgeons, radiologists, and trainees. Integration of anatomical knowledge with modern imaging techniques facilitates safer clinical practice and better patient outcomes [10].

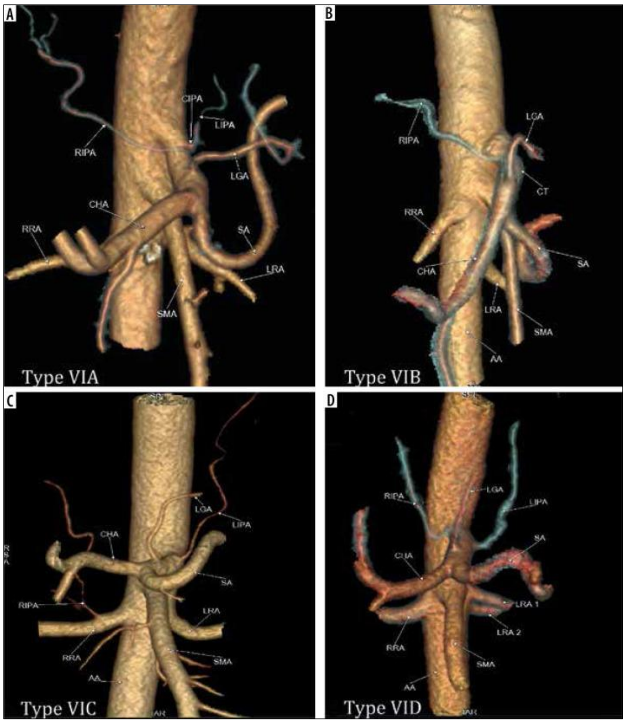

Figure 5: Three-dimensional CT angiographic reconstruction demonstrating abdominal arterial anatomy and vascular variations useful for preoperative planning

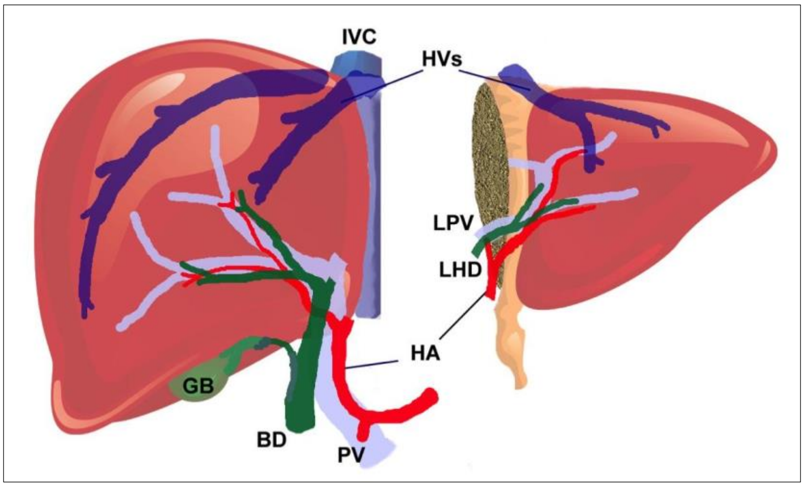

Figure 6: Clinical applications of abdominal aortic anatomy in liver transplantation, renal transplantation, vascular surgery, and endovascular interventions

Future Perspectives and Advances in Imaging

The increasing sophistication of imaging technologies has transformed the study and clinical evaluation of abdominal vascular anatomy. Multidetector computed tomography angiography (MDCTA), magnetic resonance angiography (MRA), and advanced three-dimensional reconstruction software now allow accurate, non-invasive visualization of arterial branching patterns [11].

Recent studies have demonstrated that MDCTA can detect even small accessory arteries with excellent sensitivity and specificity. These capabilities have substantially improved preoperative planning for transplant surgery, hepatobiliary procedures, and complex oncological resections [12].

Artificial intelligence and machine learning are emerging as promising tools in vascular imaging. Automated vessel segmentation and anomaly detection systems may enhance the identification of rare vascular variants while reducing interpretation time and observer variability [13].

Three-dimensional printing technology is also increasingly used to create patient-specific vascular models. Such models allow surgeons to rehearse complex procedures, improve anatomical understanding, and reduce intraoperative complications [14].

The integration of anatomical databases, digital atlases, and advanced imaging platforms may facilitate the development of individualized surgical approaches tailored to each patient's vascular anatomy. Future research should focus on large-scale population studies to establish comprehensive prevalence data across different ethnic and geographical groups [15].

Moreover, the growing field of precision medicine underscores the importance of individualized anatomical assessment. Recognition of vascular variants before intervention can improve procedural success, minimize complications, and contribute to better long-term outcomes [16-20].

Continued collaboration among anatomists, radiologists, surgeons, and biomedical engineers will be essential to further enhance understanding of abdominal arterial anatomy and its clinical applications [21-25].

CONCLUSION

Anatomical variations in the branching pattern of the abdominal aorta are common and arise from complex embryological developmental processes. Variations involving the celiac trunk, mesenteric arteries, renal arteries, gonadal arteries, suprarenal arteries, and terminal aortic bifurcation have significant implications for surgical, radiological, and endovascular procedures. Advances in imaging techniques have improved the detection and characterization of these vascular variants, enabling safer operative planning and reducing procedural complications. Comprehensive knowledge of abdominal arterial anatomy remains essential for anatomists, radiologists, vascular surgeons, transplant surgeons, and interventional specialists. Continued research and improved imaging technologies will further enhance understanding of these variations and contribute to improved patient care and surgical outcomes.

DECLARATIONS

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Conflict of Interest: The authors declare no conflict of interest.

Ethical Approval: Not applicable as this study is a narrative review based on previously published literature.

Author Contributions: All authors contributed substantially to the conception, literature review, manuscript preparation, critical revision, and approval of the final manuscript.

Data Availability: All data analyzed in this review are available in the cited published literature.

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