

## Anatomical Variations of Renal Arteries: Clinical, Radiological, and Surgical Considerations

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### Abstract

**Objective.** To synthesize the current knowledge regarding the embryological basis, anatomical classification, imaging characterization, and clinical implications of accessory renal arteries. **Background.** Anatomical variations in the renal arteries are common, affecting approximately 20-35% of the population, and have significant implications for clinical outcomes and surgical planning. Accessory renal arteries are usually terminal vessels that serve discrete renal islands with minimal collateral circulation in the body; therefore, their preoperative identification is important. However, there has been no modern synthesis of embryology, imaging, and multidisciplinary clinical treatment for these variations. **Methods.** A narrative review of the literature was conducted by searching PubMed and Google Scholar for publications from December 2015 to December 2025. MeSH terms and free-text keywords related to “accessory renal artery,” “multiple renal arteries,” “renal artery variations,” “renal vascular anatomy,” “kidney transplantation,” “renovascular hypertension,” “computed tomography angiography,” “magnetic resonance angiography,” and “endovascular aortic repair” were used in Boolean combinations. Peer-reviewed original studies, systematic reviews, meta-analyses, and case series were included. Conference abstracts, unpublished data, and non-English publications were excluded. **Discussion.** This review addresses the embryological basis and anatomical classification of accessory renal arteries; the diagnostic roles of Doppler ultrasound, computed tomography angiography, and magnetic resonance angiography; and their clinical implications in kidney transplantation, partial nephrectomy, and endovascular aortic repair, including the contested association with renovascular hypertension. Available data suggest that most accessory vessels do not independently cause hypertension, whereas stenosis of larger vessels may be a correctable etiology in selected cases. **Conclusion.** Accessory renal arteries have a significant clinical impact, primarily determined by the size of the vessels and the area of the kidney they supply. Preoperative characterization based on modern imaging can be reliable and can help plan and manage surgery for each patient. More prospective research is required to establish evidence-based principles for vessel maintenance and evaluate new technologies in this context.

**Key Words:** Accessory Renal Arteries ■ Anatomical Variations ■ Kidney Transplantation ■ Renovascular Hypertension ■ Computed Tomography Angiography.

### Introduction

Knowledge of the renal vascular system is fundamental to modern medicine. The kidneys play a crucial role in maintaining homeostasis and perform complex processes, including waste excretion and fluid and blood pressure regulation, all of which are extremely dependent on a sophisticated vascular system. Although classical

anatomy textbooks depict a single renal artery per kidney, clinical data demonstrate significant anatomical variations with significant implications for diagnostic and surgical planning and patient outcomes. These variations are common, with the most prevalent being accessory renal arteries, which introduce considerations in several medical subspecialties, including transplant surgery, interventional radiology, and vascular surgery. Embryological differentiation of the kidney

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involves a complex process of migration of this organ from its original pelvic position to the ultimate retroperitoneal position, supplemented by dynamic alterations in the arterial supply, which can lead to the survival of normally transient embryonic vessels (1).

Additional arterial vessels that supply renal perfusion (in addition to the primary renal artery) may be referred to as accessory renal arteries. These vessels enter the kidney along the main artery through the hilum or directly enter the renal parenchyma at either end of the kidney, such as the upper or lower pole. The anatomical significance of the accessory arteries lies in the fact that they tend to be terminal vessels with no important anastomotic relationships; that is, disruption of circulation by an accessory artery can cause ischemia of the renal territory. This anatomical feature is of significant importance in surgical practice, including partial nephrectomy, kidney transplantation, and endovascular procedures for aortic pathology. According to recent systematic reviews based on meta-analyses, the presence of accessory renal arteries is common across different groups in the general population, although there is some variation between ethnic groups and geographical regions (1). The discovery and description of these variations have been significantly enhanced by the development of cross-sectional imaging methods, and it is now possible to plan surgical operations before surgery.

These anatomical differences have clinical implications in various fields of medicine. In kidney transplantation, the presence of multiple renal arteries is problematic, as they may affect anastomosis, the functioning of the transplanted organ, and survival rates; however, this issue is not clearly described in the literature, with differences between studies (2, 3). Laparoscopic and robotic surgeries involve minimally invasive procedures, and in this case, preoperative mapping of vascular structures is essential to prevent unintended vessel damage. This is achieved using the latest technologies, such as three-dimensional perfusion maps, which provide new prospects for surgical planning (4, 5). In cases of abdominal aortic aneurysm endovascular

repair, there is concern about the effects of accessory renal arteries covered with endograft materials, and evidence is accumulating on the use of these materials to determine which of these arteries can be covered and which should be left uncovered (6, 7). In addition to the surgical issue, the pathogenesis of renovascular hypertension has been attributed to accessory renal arteries. However, the findings of relatively large studies with strong statistical methodologies on the same issue have yielded conflicting findings in recent years (8, 9). Although a systematic review has provided evidence on the prevalence and anatomical classification of accessory renal arteries (1), a comprehensive synthesis of imaging modalities and multidisciplinary clinical management has yet to be achieved.

Therefore, this review aims to present a modern perspective on accessory renal arteries by integrating the existing body of knowledge on their embryological origins, anatomical classification, imaging detection, and clinical management in light of recent advances in imaging technology and the accumulating body of clinical experience.

## Methods

This narrative review synthesizes current knowledge on the anatomical variations of renal arteries, focusing on accessory renal vessels and their clinical implications. A thorough literature search was performed using two major electronic databases: PubMed and Google Scholar. Combinations of Medical Subject Headings (MeSH) terms and free-text keywords were used, including: “accessory renal artery,” “multiple renal arteries,” “renal artery variations,” “renal vascular anatomy,” “kidney transplantation,” “renovascular hypertension,” “computed tomography angiography,” “magnetic resonance angiography,” and “endovascular aortic repair”. These search terms were combined using Boolean operators to maximize the retrieval of relevant articles while maintaining specificity.

The literature search was conducted between December 2015 and December 2025, given that the world has made significant leaps in diagnostic

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tools, formulated treatment practices, and clinical practice in the past decade. In the first stage, the search results were filtered by title and abstract. Potentially interesting articles were then checked in full text. The inclusion criteria were as follows: the articles had to have covered at least one of the following domains: embryological development of the renal vasculature; anatomical classification of renal artery variants; imaging detection and characterization of renal arteries; or clinical and surgical implications of accessory renal arteries. Eligible publications included original research studies, systematic reviews, meta-analyses, and clinical case series published in peer-reviewed journals. There were no limitations on the geographical area or number of patients, as the studies had to present substantial information that could be used to achieve the goals of this review. Studies with strong methodologies, large cohorts, or prospective designs were prioritized as much as possible. To conduct an additional search for relevant articles, the references of selected articles were screened.

The exclusion criteria included studies that addressed pathological conditions unrelated to anatomical variations and those in which renal vascular anatomy was mentioned incidentally and lacked substantive analysis within the scope of the review objectives. Publications not written in English were excluded due to financial constraints on translation. Non-peer-reviewed sources and unpublished data were also excluded due to concerns regarding evidence reliability. Articles on the embryological formation of the renal vasculature provide a foundation for understanding how anatomical differences are formed and preserved. The selection of studies based on their potential to accurately depict vascular anatomy was prioritized with respect to techniques applicable in modern clinical practice, namely, multidetector computed tomography angiography and magnetic resonance angiography.

Systematic reviews and meta-analyses based on multiple primary studies were appreciated because they can identify patterns and draw conclusions with more statistical power than individual studies. Data mining was narrowed to several main areas pertinent to the review goals, including prevalence information, anatomical classification frameworks, diagnostic precision of imaging tools, clinical outcomes in different surgical and interventional settings, and pathophysiology of anatomical variability and clinical presentations. The extracted information was synthesized using a narrative approach rather than a quantitative meta-analysis, given the differences in study designs, populations, and outcome measures across the covered literature. The authors independently evaluated the level of evidence of each included study according to the classification of the Oxford Centre for Evidence-Based Medicine (CEBM) 2011, as presented in Supplementary Table 1. Within this system, Level 1 corresponds to evidence from systematic reviews of randomized trials or individual randomized trials; Level 2 corresponds to randomized trials or observational studies with a dramatic effect; Level 3 corresponds to non-randomized controlled cohort or follow-up studies; Level 4 corresponds to case series and case-control studies; and Level 5 corresponds to mechanism-based reasoning, with a higher level denoting a greater risk of bias and a lower strength of the underlying evidence. Themes were used to organize the information and include the important areas of the subject, as well as to identify areas of agreement, controversial areas, and conflicting findings.

## Results

The results of the reviewed articles are listed in Table 1. based on their primary focus, such as clinical associations, surgical outcomes, and level of evidence, to provide a concise and comprehensible description of the existing evidence. Other publications are cited in the text.

Table 1. Summary of the Selected Studies on Renal Arterial Variations and Their Clinical Implications

| Study                                                   | Study Design                                            | Sample Size                                      | Clinical Focus                 | Main Finding                                                                                                                                                                                            | Evidence Level |
|---------------------------------------------------------|---------------------------------------------------------|--------------------------------------------------|--------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| Chai et al., 2008                                       | Retrospective, with surgical correlation                | N=153 donors (306 kidneys)                       | CT angiography                 | CTA findings matched the surgical anatomy in 146 of 153 donors (95%), with 96% accuracy for the number of renal arteries; missed vessels were attributed to perception errors and technical limitations | Level 4        |
| Li et al., 2021                                         | Prospective                                             | N=30                                             | Magnetic resonance angiography | Non-contrast MRA provided image quality comparable to CTA for preoperative vascular assessment                                                                                                          | Level 3        |
| Gunabushanam et al., 2024; Trunz & Balasubramanya, 2023 | Review article                                          | N/A                                              | Doppler ultrasound             | Ultrasound remains useful as an initial or follow-up tool, especially in transplanted kidneys, despite technical limitations                                                                            | Level 5        |
| Park, 2023                                              | Narrative review                                        | N/A                                              | Ultrasound                     | Renal Doppler remains valuable in selected clinical settings, but has inherent limitations in native kidneys                                                                                            | Level 5        |
| Wu et al., 2024                                         | Prospective                                             | N=200                                            | Hypertension                   | Accessory renal arteries were associated with higher blood pressure values and hormonal changes, suggesting possible physiological impact                                                               | Level 3        |
| Liang et al., 2025                                      | Propensity score matching                               | N=1113                                           | Hypertension                   | No significant relationship was found between accessory renal arteries and hypertension risk                                                                                                            | Level 3        |
| Amparore et al., 2023                                   | Prospective                                             | N=103                                            | Partial nephrectomy            | Selective arterial clamping based on vascular mapping reduced functional loss compared with main artery clamping                                                                                        | Level 4        |
| Panis et al., 2025                                      | Retrospective cohort                                    | N=251                                            | Kidney transplantation         | Sacrifice of very small accessory arteries did not impair graft function during follow-up                                                                                                               | Level 4        |
| Modi et al., 2024                                       | Retrospective                                           | N=239 (183 single artery + 56 multiple arteries) | Kidney transplantation         | No significant difference in graft survival or function between single and multiple renal artery recipients at 12 months                                                                                | Level 4        |
| Schmidt et al., 2024                                    | Retrospective                                           | N=51 (MRA) / 308 total                           | Kidney transplantation         | Ligation of small accessory arteries (mean 1.88 mm) showed comparable outcomes to anastomosis, with a slightly higher reoperation rate (15% vs. 6.5%)                                                   | Level 4        |
| Tenorio et al., 2020                                    | Retrospective review of prospectively enrolled patients | N=254                                            | Endovascular repair            | Intentional ARA coverage was associated with higher rates of AKI (21% vs. 9%) and lower freedom from renal function deterioration at 3 years (55% vs. 76%) compared with renal preservation             | Level 4        |
| Tatsuishi et al., 2024                                  | Retrospective single-center                             | N=29 (with aRA) / 331 total                      | Endovascular repair            | Coverage or embolization of small accessory vessels may be acceptable in selected patients, although some parenchymal loss occurs                                                                       | Level 4        |

## Embryological Development and Anatomical Classification

The embryological evolution of the kidney occurs via a complex chain of three consecutive structures: the pronephros, mesonephros, and metanephros. The definitive kidney develops from the

metanephros, which first forms in the sacral area at approximately the fifth week of gestation and subsequently relocates to its ultimate position in the lumbar area. During this ascent into the chest, the developing kidney receives its blood supply from the lateral splanchnic branches of the dorsal

aorta at successive lumbar and thoracic vertebral segments. During kidney ascent, the blood vessels supplying the kidney typically receive increasingly cranial aortic angles, with the vessels of the dorsal sections of the kidney undergoing regression. The principal action underlying the creation of accessory renal arteries is the failure of these transient vessels to regress completely, as demonstrated by recent anatomical studies, which have shown that accessory arteries vary considerably in patterns of vessel persistence (10).

Vasculogenesis and angiogenesis, processes linked to nephron formation, provide the basis for the molecular mechanisms that coordinate the development of the renal vasculature. The development and differentiation of endothelial cells in the developing kidney depend on signaling by vascular endothelial growth factor through its receptors. Other regulatory pathways also play roles in vascular maturation and remodeling. Recent studies on kidney organoid models have provided new insights into the intricate interactions between endothelial cells and differentiating nephrons (11). These studies have demonstrated that endothelial niches regulated by a genetically inducible mechanism can be employed to vascularize human kidney organoids with multilineage maturation, indicating that vascularization is more complex than previously thought. The interplay between molecular biological approaches and more conventional anatomical investigations has contributed to the understanding of why certain embryonic vessels persist and others regress; however, considerable individual variability remains to be fully understood.

Renal arterial variations have been classified to aid in communication with patients and facilitate surgical planning. Modern systems categorize variations based on the number of arteries supplying each kidney and their origin, and recent systematic reviews have included complete data on the occurrence of various patterns in various communities (1). According to contemporary imaging studies, the most frequent variation is a single renal artery in each kidney, observed in approximately 70–75% of individuals. Pattern II, which

depicts two arteries in each kidney, occurs in approximately 15–20% of cases, whereas three or more arteries are less common but not rare. These general trends may be further subdivided in terms of the point of arrival into the kidney: hilar arteries entering the renal hilum or polar arteries entering directly into the upper or lower pole parenchyma. Other anatomical factors include the level of origin along the aorta, the presence of an early branching pattern that can mimic multiple arteries, and the relationship of the renal vessels with those around them. A recent cadaveric study in a Slovak population reinforced these observations, detecting accessory renal arteries in 20% of cadavers, with polar vessels most frequently supplying the inferior pole, representing the predominant variant and carrying direct relevance for retroperitoneal surgical procedures (12).

### **Detection and Characterization Imaging Modalities**

The correct identification and characterization of accessory renal arteries depend on the appropriate choice and application of imaging methods. Doppler ultrasonography, an initial screening method, is a simple technique that provides real-time assessment of renal blood flow without ionizing radiation or contrast agents. Recent technical improvements have also increased the diagnostic capability of Doppler ultrasound, and current protocols focus on the methodical examination of the renal hilum and poles to optimize the detection of variant structures (13, 14). However, there are still basic restrictions, such as the deep retroperitoneal position of the kidneys, interference by intestinal gas, patient body habitus, and operator dependence. Research investigating the utility of renal artery ultrasound in contemporary practice acknowledges these drawbacks and identifies scenarios in which the method remains useful, particularly when the transplanted kidney is located superficially; hence, it can be interrogated using a high-frequency transducer (15).

Computed tomography angiography has become one of the most precise and commonly

used techniques for establishing the renal vascular anatomy in clinical practice. Contemporary multidetector CT devices can acquire isotropic data with submillimeter spatial resolution that can be reconstructed in any plane, allowing for detailed three-dimensional visualization of the anatomical details of the arteries. Clinical studies have confirmed the high diagnostic value of CT angiography in depicting accessory renal arteries and defining their anatomy. In a retrospective evaluation of 153 living kidney donors with surgical correlation, CT angiography determined the number, origin, course, and branching pattern of renal arteries with an accuracy of approximately 95%, which is important for surgical planning (16). Other data revealed by this technique include renal parenchymal abnormalities, congenital anomalies, and aortic pathology, which may have clinical management implications. The most recent focus on radiation dose optimization has led to the creation of protocols that optimize diagnostic image quality while minimizing patient radiation dose, a significant factor given the frequency with which CT angiography is used in relatively young potential kidney donors.

Another non-ionizing imaging modality is magnetic resonance angiography, which is as precise a diagnostic agent as CT angiography in most clinical cases. Current MRA methods include non-contrast methods that use the natural features of flowing blood signals and contrast methods that use gadolinium-based agents. Comparisons of MRA to CT angiography in the preoperative assessment of living kidney donors have demonstrated that the image quality of three-tesla non-contrast MRA is equivalent to that of CT angiography in the one-stop evaluation of renal vessel anatomy, without the risks of radiation or iodinated contrast (17). This has proven particularly useful in younger potential donors and patients with mild to moderate renal insufficiency, where there is a risk associated with contrast use. Nevertheless, MRA typically has a longer acquisition time than CT and may be less accurate in evaluating very small accessory vessels. Current technical innovations, such as improved reconstruction algorithms and

stronger field strengths, have further enhanced the diagnostic properties of MRA; however, practical factors, such as scanner availability and contraindications in patients with implanted devices, still affect the choice of modality in clinical practice.

The introduction of advanced imaging into the existing workflow has greatly transformed the clinical workflow, and the assessment of vascular anatomy in the pre-renal intervention stage has changed accordingly. 3D rendering and computer-assisted surgical planning based on CT or MR angiography enable surgeons to plan surgery for complex anatomy and predict challenging complications. Some newer uses have extended beyond the mere outlining of anatomy to include functionally useful information, such as the extent of the perfusion territory served by a given vessel and the amount of parenchymal volume supplied by a particular vessel (4). Such developments represent a shift toward a more focused anatomical description of the structure and function, enabling more sophisticated surgical planning and risk evaluation. The appropriate imaging modality must be selected based on clinical indications, patient-specific features, local expertise, and accessibility to CT angiography and gadolinium-enhanced MRA, which are contemporary first-line investigations for detailed evaluation of renal vascularity.

### **Clinical and Surgical Significance and Pathophysiological Implications**

The practical implications of accessory renal arteries are based on their anatomical characteristics as end-terminal arteries supplying blood to small renal fields with minimal collateral circulation. An accessory ectopic artery typically supplies a specific portion of the renal parenchyma, typically the upper or lower pole regions. The interruption of blood supply with the use of a supplementary vessel, whether due to surgery, ligation, traumatic injury, or spontaneous thrombosis, causes ischemia of the tissues that may have parenchymal infarction and scarring. Three-dimensional perfusion maps have shown that various (8 per kidney on average) branches of the artery feed the kidney.

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In partial nephrectomy, clamping only the artery nourishing the tumor results in considerably less functional injury than clamping the primary renal artery (4). The findings from this series of robotic partial nephrectomies reinforce the need to retain the accessory arterial supply whenever possible during surgery, as each accessory vessel typically maintains an invaluable supply of functional renal parenchyma. Beyond ischemic considerations, an aberrant or crossing lower-pole accessory artery may also exert a mechanical effect, compressing the ureteropelvic junction and producing extrinsic obstruction with secondary hydronephrosis. Because this presentation can mimic a ureteric calculus, the responsible vessel may be overlooked unless specifically sought on preoperative imaging (18).

The type of relationship between accessory renal arteries and systemic hypertension is an ongoing research field with developing evidence. Hypothetical pathophysiological processes underlying the association between accessory vessels and hypertension include stenosis or compression of these vessels, leading to regional renal ischemia, stimulation of the renin-angiotensin-aldosterone system, and a subsequent increase in blood pressure. A recent prospective study of 200 patients with arterial hypertension demonstrated that patients with accessory renal arteries exhibited a rise in mean blood pressure over 24 hours, elevated plasma aldosterone levels, and evidence of endothelial dysfunction compared to the corresponding controls (8). Nonetheless, a more recent study that utilized propensity score matching analysis in 1113 hypertensive patients did not demonstrate significant differences in blood pressure between patients with and without accessory renal arteries (9). The variability in these results is likely associated with variability in accessory renal artery morphology, including vessel diameter, territory served, presence of stenosis, and hemodynamic significance. Existing data suggest that the majority of accessory arteries play no role in the pathogenesis of hypertension, whereas some anatomical structures with stenosis of larger accessory vessels that serve a large portion of the renal parenchyma

can be correctable etiologic factors of renovascular hypertension in individual cases.

The clinical significance of accessory renal arteries in surgical cases depends heavily on the size of the artery and the extent of the renal territory it supplies. Small accessory vessels with diameters smaller than 2 millimeters that serve small parenchymal regions can, in carefully selected circumstances, be safely ligated without evidence of major functional sequelae. Recent single-center data from 251 kidney transplant recipients provided valuable data on this issue by comparing outcomes in patients with single versus multiple arteries, including cases in which all vessels were preserved and those in which small accessory vessels were sacrificed (19). The mean diameter of the sacrificed vessels was 1.91 millimeters, and that of the preserved accessory arteries was 3.11 millimeters. No noticeable changes in renal function were observed at 7 days, 6 months, or 12 months after transplantation. These results imply that extremely small accessory branches do not necessarily require maintenance during transplantation, thereby simplifying the technical aspects of the transplantation process without compromising graft functionality. However, larger accessory vessels, particularly those over 3 millimeters in diameter or supplying large areas of the pole or other valuable parts of the graft, are particularly worth preserving or reconstructing to achieve optimal graft function, as supported by several retrospective studies of transplant outcomes (2, 3).

The existence of accessory renal arteries also has implications for interventional procedures such as the repair of endovascular aortic aneurysms. The use of accessory renal arteries to cover endograft placement raises the issue of potential resultant ischemia and renal dysfunction. A thorough case-based review of fenestrated-branched endovascular aortic repair revealed that intentional coverage of accessory renal arteries with a mean diameter of approximately 2.7 millimeters was associated with foci of renal infarction on post-procedural imaging, a threefold higher incidence of acute kidney injury (21% vs. 9%,  $P=0.02$ ), and a significantly greater decline in renal function at 3

years compared with patients in whom complete renal preservation was achieved (6). More recent studies examining the impact of accessory renal artery embolization in the context of conventional endovascular aortic repair have also indicated that coverage of accessory vessels can be reasonable in a few patients (albeit with some anticipated parenchymal loss) (7). The clinical effect appears to be related to the diameter of the covered vessel and the area of the parenchyma supplied by vessels larger than 4 millimeters, which are more likely to result in a clinically significant functional deficit. These considerations are applied in the risk-benefit analysis when planning endovascular aortic interventions involving complex renal arteries.

### **Surgical and Interventional Considerations in Kidney Transplantation**

Given their accessibility, the clinical scenario in which accessory renal arteries are most likely to cause technical and functional challenges is during kidney transplantation. An example of such an issue is the presence of multiple renal arteries in donor kidneys, which occurs in approximately 20–30% of living donor nephrectomies, according to current imaging data. Therefore, decisions concerning vessel handling during procurement and implantation are necessary. Examples of technical options include individual anastomosis of each artery to the recipient vessels, a common arterial patch (using the donor aorta), or selective ligation of small accessory arteries, depending on the size and territory served. New findings on the outcomes of different management strategies have helped to optimize surgical management techniques. Retrospective studies have been conducted on several occasions to determine whether the complications or long-term outcomes of multiple-artery kidneys are worse than those of single-artery kidneys. Although some previous studies have shown that delayed graft function and vascular complications are higher, more recent studies that used superior surgical techniques have not revealed any significant difference in long-term graft

survival, provided that proper management measures were followed (2, 20).

The technical approach to reconstructing kidneys with multiple renal arteries is continuously evolving as microsurgical capacity advances, and our understanding of which vessels should and should not be conserved is deepening. Half of the bootstrap is performed using traditional techniques with distinct anastomoses to the recipient iliac vessels or a Carrel patch using a donor aorta with all arterial origins. A recent study investigating microsurgical strategies for lower polar arteries to the inferior epigastric artery showed positive results with preserved perfusion of the polar areas and tolerable grafting operations over the long term (5 years) (21). These methods demonstrate that a complex arterial anatomy does not necessarily imply a preconception of successful transplantation in humans; rather, it represents an additional technical complication and prolonged ischemia due to multiple anastomoses. Therefore, these methods must be considered with caution when evaluating donors and planning surgical revascularization. Normothermic machine perfusion methods may offer new opportunities for the management of kidneys with complex vascular anatomy, given their potential for long preservation periods and preoperative functional evaluation (22).

When renal surgery is involved, minimally invasive surgical procedures, such as laparoscopic and robotic surgery, require accurate knowledge of the vascular anatomy to prevent unintended vessel damage. Laparoscopic surgery has a small working space and a low level of visualization; therefore, there is a high probability of injuring unidentified accessory vessels. The possible benefits of robotic surgical systems include enhanced visualization through the use of three-dimensional, high-definition optics and enhanced dexterity, enabling more precise identification of vessels and their preservation. Detailed analyses of robot-assisted surgical methods for vascular surgery have described their development and further customization to intricate renal vascular anatomy (5). Preoperative CT or MR angiography is a significant component of

planning minimally invasive procedures, enabling surgeons to predict anatomical variations and design appropriate vessel management strategies. Partial nephrectomy, a procedure involving the partial removal of the kidney, can be performed using intraoperative techniques that reduce the degree of ischemia. Recent studies have shown that computerized three-dimensional visualization of perfusion territories enables selective arterial clamping based on preoperative mapping. This approach allows ischemia to be confined to the area of the kidney being resected (4).

The trade-off between the technical feasibility of preserving the vessel and the anatomical constraint of deploying the endograft is the management of accessory renal arteries in endovascular aortic repair. It is possible to preserve renal vessels in a substantial proportion of juxtarenal and thoracoabdominal aneurysm cases using fenestrated and branched endograft designs; however, the technical difficulty of the designs increases substantially with each vessel that must be included. Decisions regarding the coverage of small accessory renal arteries during endograft placement depend on the vessel size, supplied renal territory, baseline renal function, and technical capability to maintain the vessel. Currently, evidence based on large series indicates that accessory vessel coverage of up to 3–4 millimeters may be acceptable in patients with normal baseline renal function; however, a small amount of focal parenchymal loss can be expected and should be discussed with patients preoperatively (6, 7). The preservation of larger accessory vessels, particularly those whose coverage may span a significant region of the poles, should be considered technically feasible, as such coverage may cause clinically significant functional impairment, particularly in individuals with underlying renal failure. Recent case reports have described the option of using accessory renal arteries in branched endograft designs when preservation is deemed vital; however, this approach is associated with a significant increase in technical complexity (23).

## Discussion

The existing literature on accessory renal arteries indicates that although their clinical significance has been better elucidated, there remain areas requiring further investigation. The technical problem of preoperative detection and characterization of accessory renal vessels has been partially solved by modern imaging methods, and we can now plan the operation using detailed information about the vessel anatomy rather than finding them during the operation (10, 16, 17). With the easy accessibility of CT and MR angiography, complete preoperative vascular assessment is now possible in almost every patient undergoing renal surgery or in potential kidney donors. However, outstanding questions remain regarding how different clinical situations should be managed, particularly regarding which accessory vessels should be retained and which can be sacrificed without any functional consequences. Recent large-scale studies have begun to provide answers to these questions by rigorously comparing the results with alternative management approaches (8, 9, 16, 19); however, additional research with longer follow-up and more complex functional evaluations is needed to enhance the evidence base.

The relationship between accessory renal arteries and renovascular hypertension indicates the difficulty in interpreting the association between anatomy and clinical concepts. Although plausible theoretical mechanisms have been proposed linking regional renal ischemia caused by accessory artery stenosis to hypertension, clinical evidence supporting this association is lacking, and recent well-designed studies have yielded conflicting results (8, 9). This variability is likely due to the heterogeneity of the accessory artery structure and the multifactorial nature of hypertension pathogenesis. Further studies with more sophisticated phenotyping of accessory artery parameters, such as the measurement of distal renal perfusion volume, extent of stenosis by both anatomic and functional features, and local perfusion distribution, could be used to define which anatomic features are indeed risk factors for hypertension. Such

investigations can inform screening measures and help identify patients who could be treated with interventional methods for accessory vessel stenosis, which is controversial due to conflicting evidence on causality.

The dilemma of whether to treat accessory renal arteries in kidney transplantation lies between technical considerations and optimal function. Although recent evidence suggests that sacrificing small accessory vessels may not have a substantial functional effect (19), it is necessary to balance this strategy with the overall philosophy of maintaining all viable vascular supply, as long as technical feasibility exists (2, 3). Technological advances in microsurgical reconstruction that enable complex reconstruction of multivessel arterial anatomy have expanded the possibilities for repairing multiple vessels in the kidney, although these microsurgical techniques are complex and complicate surgery. The literature would also be improved with more prospective studies that carefully compare various reconstruction strategies with respect to vessel characteristics, details of the surgical technique used, and functional outcomes of reconstruction with advanced methods, such as nuclear medicine studies and biomarkers. These studies would be useful for providing evidence-based guidelines on the most appropriate timing for using various management strategies, rather than the current situation, in which the choice of surgeon and institution guides management.

This review has several limitations. First, only two databases (PubMed and Google Scholar) were searched, potentially missing publications indexed in other databases. Second, language bias may have been introduced by the exclusion of publications written in languages other than English. Third, as a narrative review, the formal quality appraisal instruments used in systematic reviews were not employed, and the evidence synthesis was subject to some selection and interpretation bias. Fourth, most of the evidence available on the subject is based on retrospective studies and observational series, which, by nature, limit the validity of the findings regarding causal relationships and best management practices. These limitations

should be considered when interpreting the findings of this review, and they explain why prospective, well-designed studies are necessary to further elucidate the clinical importance of accessory renal arterial variations.

The advent of new technologies, including state-of-the-art three-dimensional visualization, virtual-reality-guided surgical software, and machine-learning approaches to anatomical classification, can improve the detection and management of accessory renal vessels. Using detailed anatomical data, computational modeling of renal perfusion may have the potential to predict the functional implications of various surgical plans, providing a foundation for individualized treatment. The use of artificial intelligence in image interpretation can reduce interobserver variability in the detection and characterization of vascular variations and the potential detection of small anatomical changes related to clinical outcomes. The recent use of automated perfusion territory mapping in robotic partial nephrectomy demonstrates that possibilities exist; however, the development of other clinical applications, such as transplantation and endovascular repair, requires further development and validation (4). With the increasing sophistication of these technologies and their broader availability, more individualized solutions may be found to address anatomical variations based on foreseeable functional effects, rather than arbitrary presence or size thresholds. Nevertheless, technological innovations must undergo rigorous clinical trials that demonstrate enhanced benefits to justify their use in practice and the costs incurred.

## Conclusions

An example of an anatomical variation that is significant across many fields of clinical practice is the accessory renal artery. These differences in the persistence of the normally temporary mesonephric vessels are explained by their embryological origin, which accounts for their typical distribution and functional properties as terminal arteries in the renal territories. Recently, modern imaging

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modalities, particularly CT and MR angiography, have provided reliable methods for the preoperative detection and characterization of renal vascular anatomy, enabling informed surgical planning and risk assessment. Recent large-scale studies have improved our understanding of the clinical importance of accessory renal arteries, demonstrating that vessel size and renal parenchyma volume served are significant factors in determining the need for preservation. Small accessory vessels may not require treatment in certain clinical circumstances and often have no significant functional consequences; however, larger vessels that supply a substantial renal territory are typically important for preserving the best renal function.

The treatment of accessory renal arteries requires careful evaluation of the specific clinical situation, anatomy of the involved vessels, and level of technical skill available. In kidney transplantation, good long-term outcomes are evident with multiple renal arteries, which are clearly acceptable as a practice, although there is extra technical complexity that must be considered in the choice of donors. The association between accessory renal arteries and renovascular hypertension remains poorly understood, as recent rigorous studies have produced conflicting findings. This suggests that further research incorporating advanced phenotyping is required to determine which anatomical configurations are associated with an increased risk of hypertension. To address these gaps, future studies should prioritize prospective multicenter studies that report standardized vessel parameters, such as diameter, supplied parenchymal territory, and perfusion volume, alongside longer-term functional endpoints, so that evidence-based thresholds for vessel preservation can replace the current institution-dependent practice.

#### What Is Already Known on This Topic:

*Accessory renal arteries are among the most common variations of the renal vasculature and are relevant to kidney transplantation, partial nephrectomy, and endovascular procedures. Their prevalence and anatomical patterns are well described, and modern cross-sectional angiography reliably depicts them before surgery.*

#### What This Study Adds:

*This review integrates current evidence on the embryology, classification, imaging, and multidisciplinary management of accessory renal arteries and clarifies areas of ongoing uncertainty, such as their contested association with hypertension. It underscores the preservation of functionally significant vessels and outlines concrete directions for future standardized prospective research.*

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**Conflict of Interest:** The authors declare that they have no conflict of interest.

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