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INTEGRATED STUDY MASTER´S THESIS

Variations in topography of renal blood vessels (a study with bodies donated to Vilnius University)
Inkstų kraujagyslių topografijos variacijos (tyrimas su Vilniaus universitetui paaukotais kūnais)

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1 Abbreviations

IVC – inferior vena cava

RLRV – retroaortic left renal vein

CLRV – circumaortic left renal vein

LRV – Left renal vein

CT – Computer Tomography

MRI – Magnetic Resonance Imaging

2 Summary

Renal vasculature variations are frequently observed and have significant clinical implications, for instance in kidney transplantation. This thesis aims to establish a clear classification of the renal arterial and venous variations, based on existing literature while considering their clinical relevance and embryological basis. The different types and frequencies of these variations are compared to the newly gathered cadaveric dissection data. Furthermore, this pilot data set provides initial insights into the frequency of variations within the Lithuanian population, facilitating comparisons with data from other countries and ethnic groups.

To analyse renal variations, a study with donated bodies was conducted at Vilnius University Faculty of Medicine. Autopsy provides an advantage due to its higher accuracy compared to indirect observation via imaging modalities. For data collection, both kidneys, along with their arteries and veins, were examined for anatomical variations. The number, origin, and branching patterns of the renal vessels were recorded and systematically analyzed. These findings were then compared to existing data in the literature to identify similarities, differences, and potential population-specific trends.

Within the data set, it was observed that 8 out of 23 renal arteries (34.7%) exhibited no variation, displaying a single renal artery. Among the variations, aortic superior polar arteries (21.7%) were more frequent than their inferior counterpart with 4.3%. Perihilar branching, where the artery bifurcates before entering the kidney parenchyma, occurred in 39.1% of cases, though not considered a true variation. Contrarily, early branching, which was the most frequent variation with 30.4%, is considered an actual variation and of special clinical importance especially for surgical interventions. Lastly, arterial branches from the renal artery supplying the poles of the kidney called perihilar superior and inferior polar arteries, had a frequency of 26% and 0% respectively. Regarding renal vein variations, the left and right kidneys were further distinguished. On the right side 9 out of 11

(81.8%) samples had a single renal vein and 18.2% an additional renal vein. No cases of abnormal reflux and rare type were observed. Variations on the left side were more prevalent, and more variants were distinguished, additionally displaying circumaortic and retroaortic left renal vein as well as late venous confluence. With the exception of the rare type, all variations of the left renal vein were found once, corresponding to a frequency of 8.3%. Consequently, 50% of left renal veins (6 out of 12) showed no variations.

The thesis emphasizes that renal variations are common while highlighting their clinical significance. It can be concluded that the development of a standardized classification system for these variations is essential to improve consistency across the literature. Furthermore, additional research is needed to investigate variations across different ethnic groups, including the incorporation of data from Lithuania.

3 Keywords

Renal Vasculature Variations, Multiple Renal Arteries, Cadaveric Study, Renal Artery Variations, Renal Vein Variations, Ethnical Variance

4 Introduction

The standard anatomy describes a single renal artery and vein. However, renal vasculature has a considerably high variance for renal arteries as well as veins which is due to their embryological development. Across the literature, there are many different classifications of renal vasculature variations present. Also, previous studies have found ethnical differences in occurrence of renal variation. According to the commonly referred to cadaver study of Sampaio and Passos (1) only 55.3% exhibit one hilar artery which is the anatomy traditionally described. Renal vein variations are also commonly described and the literature often distinguishes between right and left renal vein variations. In general, a meta-analysis by Hostiuc et al. (2) found that 16.7% of kidneys have multiple renal veins. Other renal vein variations like circumaortic and retroaortic left renal vein have specific clinical relevance, especially regarding nutcracker syndrome. Renal artery variations are also of clinical relevance for instance for resistant hypertension and operative difficulty of kidney transplantation.

This thesis aims to evaluate the renal vasculature variations of cadavers donated to Vilnius University. Based on the findings, a conclusive classification is developed that not only provides a clear description but is also easily understood by other researchers. Furthermore, baseline knowledge is established about the prevalence of renal artery variations within Lithuania. The findings are related to their clinical relevance and embryological basis.

5 Literature Review

5.1 Renal Anatomy and Basic Physiology

The kidney typically receives approximately 22 percent of the cardiac output, filtering 1100 ml of blood per minute. The kidneys perform several functions crucial to maintaining homeostasis, such as regulating the acid-base balance, glucose homeostasis, and fluid and electrolyte balance. Additionally, they play a role in the production of erythropoietin, activation of vitamin D, filtration of waste products, and regulation of blood pressure (3).

In Grey´s Anatomy the kidney is described to be in a primarily retroperitoneal position covered by extra-peritoneal tissue. Both kidneys have a similar size and shape though the right kidney is more plumb, slightly shorter and further from the midline of the body. The superior pole of the right kidney is positioned in front of the 12th rib, whereas the superior pole of the left kidney lies anterior to both the 11th and 12th ribs. Medially of each kidney is the hilum which contains the vasculature, lymphatics and nerves. The structures present at the hilum continue internally to the renal sinus which then supply the different segments of the kidney (4).

The main macroscopic anatomical structures of the unit are the renal cortex, medulla and pelvis. The renal cortex is at the outer region of the kidney containing the bowman capsule of the nephron as well as the proximal and distal tubule. Further to the center of the kidney is the medulla with its renal pyramids which contain the loop of Henle and collecting duct in which the urine is concentrated. From the papilla of the renal pyramid the fluid empties into the minor and major calyces funnelling into the renal pelvis which is connected to the ureter that further transports the urine (3).

Traditionally, the kidney is supplied by a single renal artery which branches from the abdominal aorta. Usually, they originate between LI and LII below the superior mesenteric artery. The right renal artery is mostly located lower than the left renal artery and passes posteriorly to the inferior vena cava which is why it is of greater length. Close to the hilum of the kidney, the renal artery divides into the anterior and posterior branch, which are often called presegmental arteries. They then further split into segmental arteries that correspond to the regions of the kidney they are supplying which are apical, upper, middle, inferior and posterior. This segmentation has limited or no collateral arterial circulation making them all essential for adequate supply of the kidney and therefore should not be easily ligated in surgery (4,5).

Both veins are located anteriorly to their respective arteries. The left renal vein connects to the vena cava by passing anteriorly of the aorta and posteriorly of the superior mesenteric artery which imposes the risk of its compression. Contrarily to the renal arteries, the left renal vein with an average length

of 8.5 cm significantly longer than the right renal vein with about 2-2.5 cm length. The arcuate and interlobar veins drain the renal cortex and thereby are interconnected by anastomoses displaying no segmental arrangement in contrast to the renal arteries. This in conclusion allows ligation of a venous branch as it does not affect the drainage of the kidney (4,6).

5.2 Embryology

The kidneys originate from intermediate mesoderm, giving rise to the urogenital ridge at approximately 4 weeks of gestation. This ridge splits into the nephrogenic cord and gonadal ridge which form the urinary and reproductive system, respectively. During the development of the urinary system, there are three stages: pronephros, mesonephros and metanephros. First, pronephros forms consisting of a pronephric duct and tubules that are nonfunctional and regress at 5 weeks of gestation. It´s role in kidney development is not well understood (7,8).

The mesonephros first becomes apparent at week 4 and regresses until 8 weeks of gestation. During this stage, the mesonephric duct (also known as the Wolffian duct) forms. Additionally, around 40 pairs of mesonephroi develop, with approximately 20 becoming functional excretory units located at L1-L3. The vascular supply of intermediate kidneys is maintained by the urogenital rete arteriosum or the mesonephric arteries, which ultimately converge into a single branch known as the renal artery. If more than one mesonephric artery persists, they form multiple renal arteries. The mesonephric duct and tubules are only temporary functional and degenerate in females while forming the vas deferens, seminal vesicles, and ejaculatory duct in males (7,8).

Lastly, metanephros is the third stage through which the permanent kidneys are formed. Its development starts by the 5th week of gestation and becomes functional by week 9-12. The process initiates when the mesonephric duct induces the metanephric blastema to secrete glial-cell-derived neurotropic factor (GDNF). This factor stimulates the mesonephric duct to form the ureteric bud. When the ureteric bud enters the adjacent metanephric mesenchyme, it causes the induction of the ureteric bud branching also called ureteric tree. This ultimately leads to the formation of collecting ducts, calyces and the renal pelvis as well as the ureter which forms from the portion of the ureteric bud that is outside of the metanephric mesenchyme. Further, nephrogenesis is initiated here by induction of committed metanephric mesenchyme cells through the tips of the ureteric tree leading to the formation of renal vesicles that differentiate into nephrons. The branching cascade continues from 6-36 weeks of gestation. Therefore, preterm birth, low birth weight and intrauterine growth restrictions affect renal function (8,9).

While the kidneys develop, they also migrate from the pelvis to T12-L1 inferior to the adrenal glands. This process happens from the 6th to 9th week of gestation. To reach its final position, they rotate from

their ventral position 90 degrees medially. If they fail to relocate, it causes a pelvic/ectopic kidney or a horseshoe kidney where a variation in blood supply is displayed. Additionally, in a horseshow kidney the kidneys fuse at the inferior pole below the mesenteric artery forming its characteristic U-shape (8,10).

Renal vasculature variations are rooted in their embryological origin, because the kidneys are supplied by transient vasculature that degenerate while the kidney migrates to its final position. Thereby the vasculature sometimes does not degenerate and therefore generate vasculature variations (11).

Regarding renal arteries, during mesonephros (described above) the vascular supply is maintained by 9 pairs of lateral mesonephric arteries that arise from the dorsal aorta. Those 9 pairs are divided into 3 groups namely cranial (1^{st} and 2^{nd} pair), middle (3^{rd} -5^{th} pair) and caudal (6^{th}-9^{th} pair). The central hilar renal artery arises from the middle or first caudal group. If there are any other arteries remaining, it results in multiple renal arteries (6,11).

Within the venous drainage system, there is an irregular network of capillaries. These do either develop into veins or disappear. The early venous system develops around the aorta and is closely related to the development of the inferior vena cava. The posterior cardinal veins are responsible for the early drainage of the lower body and regress later. This is followed by the subcardinal veins that drain the mesonephros and are developing into the renal and gonadal veins. At the 6^{th} week the supracardinal veins develop that mainly contribute to the infrarenal IVC and azygos/hemiazygos system. Anastomoses between subcardinal and supracardinal veins form the dorsal arch of the aortic collar from which the renal veins develop. At the beginning there are two, a ventral and a dorsal vein. During further development, the dorsal veins regress. If the ventral veins regress instead of the dorsal once, it causes a retroaortic left renal vein. Also, if none of them regress a circumaortic renal vein develops. In case of multiple renal veins, they originate from persistence of embryonic venous anastomoses and can vary widely. Further, the suprarenal inferior vena cava forms by the persistence of the right supracardinal vein and the concurrent regression of the left supracardinal vein. When the left supracardinal vein persists, it causes the IVC to be on the left side crossing over to the right side at the level of the kidneys. In case both the left and the right supracardinal veins persist it causes the formation of a double IVC. In very rare cases the IVC can be absent if the right supracardinal veins fail to develop causing an alternative drainage through the azygos and hemiazygos veins (12).

5.3 Diversity of Classification and Data Collection in Renal Arteries

The following variations are traditionally found at the renal vessels including all variations from the aorta until the hilum of the kidney, excluding the presegmental or segmental arteries of the kidney.

Firstly, there can be multiple renal arteries originating from the aorta. A maximum of 5 renal arteries in one kidney have been described by Sampaio and Passos (1). These multiple arteries can either supply the hilum or one of the poles of the kidney. Secondly, branching of renal arteries has been reported. These branches can also supply either the hilum or the poles of the kidney (1,6).

Two different branching patterns are sometimes distinguished in the literature, as differentiating between them has important clinical applications. Firstly, extrahilar or perihilar branching is a broad term for a renal artery that splits before it reaches the hilum. Secondly, the term early branching is used to describe renal arteries that branch within 1.5 cm of their origin. They then enter the renal hilum as a segmental artery. It should be noted that these variations can also occur simultaneously, for example when multiple renal arteries are present with branching in one of them (13,14).

In addition to the variations found traditionally there have been various rare cases of kidney vasculature anatomy. For instance, there are reported incidences of the renal artery originating from iliac, lumbar, middle sacral, celiac and superior and inferior mesenteric arteries (6).

In the literature the nomenclature for these variations is not standardized, which makes it challenging to compare data from different studies. The same type of anatomical variation can in essence be classified in different depending on the authors choice. To get an overview of classifications and their advantages and drawbacks, multiple approaches are described below.

An important attempt to standardize the nomenclature has been made by Negromonte et al. (15) who focused on the terminology generating no analysis of the prevalence itself. Nomenclatures from multiple sources were compared, among them a study from Satypal et al. (16), which analyzed the occurrence and number of additional renal arteries, excluding their anatomical peculiarities, calling any variation additional artery. Negromonte et al. bases their classification mainly on a study from Sampaio and Passos (1). There, it was generally distinguished between hilar and extra-hilar arteries which were further separated into superior and inferior polar artery. If there was any perihilar branching, called precocious bifurcation by Sampaio and Passos (1), then it was named “superior or inferior pole extra-hilar branch” based on the pole of the kidney supplied by the vessel. Furthermore, the study defined three groups describing kidneys with either one, two or three arteries originating from the aorta (1,15,16).

In 2020, Abuelnour et al. performed a meta-analysis of 51 studies to both group anatomical variations in renal arteries and analyze prevalence of individual types. They chose a different categorization based on the region of the kidney that is supplied by the artery. This classification excludes early branching of the renal artery, defining accessory hilar arteries as those originating from the aorta.

Further qualification of the accessory arteries was done by comparing their calibers to determine the dominant artery and labelling them “co-dominant” if the calibers were similar. The inferior and superior polar renal arteries that originated from the renal artery itself were labeled polar branches to acknowledge their origin. This approach allowed the authors to compare data from a range of studies, but sacrificed the level of detail of the categorization proposed by Negromonte et al. (15,17).

A study from Cases et al. also offered a detailed classification differentiating types and patterns of variations. They are using five different types: The single renal artery termed hilar artery and arteries supplying the upper or lower pole, of either aortic or renal arterial origin. Further the authors offer a more detailed classification of the number of arteries supplying the kidney, describing five patterns of one to five arteries (reported by Sampaio and Passos), although the samples analyzed by the authors themselves only exhibited up to four arteries (1,18).

An example detailed classification example by Budhiraja et al, based their it on works of Merklin and Michels (19). In the study any variations in vasculature, apart from a single artery originating from the aorta, was classified as supernumerary renal artery, with them being grouped into aortic or renal origin. The term hilar supernumerary artery was introduced, which includes multiple arteries originating from the aorta as well as a bifurcation of the renal artery itself (elsewhere classified as early hilar branching). Arteries supplying the poles of the kidney were termed upper/lower polar supernumerary arteries. A disadvantage of the classification used in this study is the fact that branching arteries were not further classified as extrahilar branching and early branching arteries, despite the clinical significance of this differentiation (20).

Early branching is of special importance for surgical procedures such as transplantation as a minimum arterial length of 1.5-2 cm is necessary. Within the literature there are multiple terms used for extrahilar branching and early branching. For instance, Kumaresan et al. use the term “early division” for early branching and define it as a renal artery that branches less than 1.5 cm from its point of origin. Other terms commonly used for early division are precocious bifurcation and prehilar branching. Different opinions also exist on the distance between branch and origin that should serve as threshold to classify an early branch as opposed to an extrahilar branch. Studies both from Sampaio and Passos and Aremu et al. choose 1 cm as the limit. In contrast, Türkvatan et al. define it as 1.5 – 2.0 cm from the aorta, possibly because of its surgical relevance.

Instead of extrahilar branching the term prehilar branching is also used, for example by Jarral et al. These different terms highlight the fact that there is no unified classification for arteries branching from the main artery (1,13,14,20–23).

There are also different prevalences reported in the literature for the anatomical variations. Looking at the prevalence of different anatomical variations reported in the literature, there are discrepancies between individual studies. A striking difference is found between the studies of Budhiraja et al and Abuelnour et al. The prevalence of a single renal artery without branching reported by Budhiraja et al is only 40.1%, compared to the 81.05% reported by Abuelnour et al. A possible explanation is the fact that Budhiraja only analyzed 37 cadaver samples from northern India, while Abuelnor et al performed a meta-analysis over studies from different countries. This suggests possible ethnic variations as a contributing factor to these differences (17,20).

Table 1 Examples of Nomenclature of Renal Arteries

Article	**Nomenclature**	**Results**
Abuelnor et al. (17)	**Main Renal Artery (MRA)** **Accessory Hilar Arteries (AHA):** additional renal artery supplies hilum **Superior polar Artery (SPA):** artery supplies superior pole **Inferior Polar Artery (IPA):** artery supplies inferior pole	Systematic Review. No data collection of authors themselves. Total: 11563 MRA: 9372 (81.05%) AHA: 1385 (11.97%) SPA: 722 (6.46%) IPA: 531 (6.24%)
Cases et al. (18)	**Hilar artery:** supplies hilum **Aortic upper/lower polar artery:** artery from aorta to poles of kidney **Hilar upper/lower polar artery:** artery from hilar artery to poles of kidney Five types (a-e): a) Single hilar artery b) Hilar upper polar renal artery c) Aortic upper polar renal artery d) Aortic lower polar renal artery e) Hilar lower polar artery 5 patterns (I-V): I – single artery – V five arteries	Types: Cadaver: a 79%, b 10.5%, c 4.7%, d 3.5%, e 2.3% CT: a 95.3%, b 1.8%, c 1.7%, d 1.2%, e 0.07% Pattern: Cadaver – I 40/86, II 18/86, III 2/86, IV 2/86 CT – I 1023/1166, II 143/1166
Sampaio and Passos (1)	**Hilar artery:** starts aorta enters hilum of kidney	Cadaver study 266 pedicles: 1 hilar artery 55.3%

Table 1 Examples of Nomenclature of Renal Arteries

	Hilar artery with precocious bifurcation: branching within 1 cm of aorta **Superior/inferior polar artery:** artery supply from aorta to poles of kidney **Hilar artery with superior/inferior pole extra-hilar branch:** artery supply from hilar artery to poles of kidney	1 hilar artery with 1 superior pole extra-hilar branch 14.3% 2 hilar arteries 7.9% 1 hilar artery with 1 superior polar artery 6.8% 1 hilar artery with 1 inferior polar artery 5.3% 2 hilar arteries with 1 superior pole extra-hilar branch 3.4% 1 hilar artery with a precocious bifurcation 2.6% 3 hilar arteries 1.9% 2 hilar arteries with 1 superior polar artery 1.1% 2 hilar arteries with 1 inferior polar artery 0.7% 2 hilar arteries with 1 superior polar artery and 1 inferior polar artery 0.4% 3 hilar arteries with 1 superior polar artery and 1 inferior polar artery 0.4%
Negromonte et al. (15)	**Single hilar artery:** starts aorta enters hilum of kidney **Double or multiple renal artery:** higher caliber termed dominant, smaller accessory **Extra-hilar polar branch:** branch of renal artery that penetrates pole of kidney **Polar artery:** branch of the aorta that penetrates pole of kidney **Pre-segmental hilar branch:** branching of hilar artery before hilum,	Literature review. No data collection by the authors

Table 1 Examples of Nomenclature of Renal Arteries

	further division in dominant and accessory **Hilar artery with early bifurcation:** single branch of aorta with less than 1 cm of length	
Budhiraja et al. (20)	**One artery** **Aortic origin/ Renal origin:** **Hilar supernumerary renal artery (HSA):** supply hilum of kidney **Upper polar supernumerary renal artery (UPSA):** supply upper pole of kidney **Lower polar supernumerary renal artery (LPSA):** supply lower pole of kidney	Cadaver study 74 kidneys: One artery 40.5% Aortic origin 47.3%: HSA 21.6%, UPSA 14.9%, LPSA 10.8% Renal origin 12.2%: HSA 8.1%, UPSA 2.7%, LPSA 1.4%

5.4 Diversity of Classification and Data Collection in Renal Veins

There are various types of renal vein variations due to its complex embryological development. The origin of these variations is detailed in the Embryology section. Generally, the right renal vein is a single vein in approximately 85% of the population and, with its 2-2.5 cm length, is significantly shorter than the left vein with about 8.5 cm in length. Normally, there is no further drainage into the right renal vein compared to the left which drains the left adrenal vein superiorly that has further tributaries from the inferior phrenic and capsular veins. Inferiorly the left renal vein drains the left gonadal vein. Further, in about 75% of cases the left renal vein is fed by the retroperitoneal veins including the lumbar, ascending lumbar and hemiazygos veins. This difference in anatomical factors causes many authors to classify the right and left renal vein separately (6).

In the paper of Hostiuc et al. they focused on the three main renal vein variations being retroaortic renal vein, circumaortic renal vein and multiple renal veins. This was necessary because the meta-analysis required a classification where many articles can be compared. In the different studies that were analysed in this meta-analysis, there were varying prevalences for the variations. The retroaortic renal vein was found to have a prevalence of under 1% up to almost 10% with a mean of 3% while

the circumaortic left renal vein varied from below 1% to more than 15%. The latter's mean value is 3.5%. Further, the frequency of multiple renal veins also varied, specifically from 2% to over 40%. Their statistical analysis concluded that a mean prevalence is 16.7% with a much higher occurrence on the right side (16.6%) than on the left (2.1%). The data was collected with CT, Surgery, Autopsy, MRI, Laparoscopy, Color Doppler ultrasonography, phlebography and venogram which partly influenced the number of variations being found because of their different accuracy (2).

In comparison to Hostiuc et al., Zhu et al. focussed on creating a detailed classification of the renal vein variations instead of simplifying their classification for the purposes of data analysis. The left renal vein was divided into five types (type I-V) and further subdivided into A and B depending on their drainage (described in Table 2 Examples of Nomenclature of Renal Veins). The less frequent variations on the right kidney drainage are also reflected by only 3 types (type 1-3) that group all variations apart from additional renal vein and an abnormal reflux through paravertebral veins, as rare type. The most frequent variation present was Type 1 being an additional right renal vein with 18.7% while on the left-side type I and II were equally the most common with 2.1% each. Both values are lower than the mean value found in the meta-analysis of Hostiuc at al. (2,24).

Because the variations vary widely some articles for instance Karaman et al and Aljabari et al. only classify the left renal vein especially its position respectively to the IVC. Similarly to Zhu et al., Aljabari et al. classified the left renal vein variations in detail. They further included horseshoe kidneys as a variant and acknowledged whether situs inversus was present. Even though they analysed 1788 cases with contrast-enhanced CT, they did not any case of situs inversus. With 1.62% of cases displaying a circumaortic left renal vein, it is slightly below the 3.5% found in the meta-analysis of Hostiuc et al. Karaman et al. focussed on only classifying the retroaortic left renal vein which also included the circumaortic left renal vein (type III) as it also passes inferiorly of the aorta. It then further classifies the variation according to where the veins drain into from orthotopic which is type I to joining at the level of L4-L5 (type II) and the left common iliac vein (type IV). In total, they found variations of retroaortic veins in 3.6% of the patients with type I being the most frequent and type IV the least. They further concluded that the urological symptoms where statistically significant ($p<0,05$) more frequent in patients with a retroaortic left renal vein, making it of special clinical relevance. Also, they found no statistically significant difference in female and male frequency of RLRV. Both Karaman et al. and Aljabari et al. with prevalences of 3.6% and 3.18%, respectively, in retroaortic left renal veins are within the confidence interval of 2.4%-3.6% from the meta-analysis of Hostiuc et al. (2,25,26).

Table 2 Examples of Nomenclature of Renal Veins

Article	Nomenclature	Results
Hostiuc et al. (2)	Circumaortic renal vein Retroaortic renal vein Double/multiple renal veins	Meta analysis Retroaortic renal vein 3% Circumaortic renal vein 3.5% Multiple renal veins 16.7%
Zhu et al. (24)	Left renal vein- LRV: **Type I circumaortic LRV** IA: single LRV divides into two branches IB: two LRV arise separately hilum **Type II retroaortic LRV:** IIA: from hilum to IVC IIB: from hilum to common iliac vv. **Type III abnormal reflux:** IIIA: two renal veins, one drain from the pole of the kidney IIIB: single or multiple LRV drain left sided IVC, vena hemiazygos or left limb of double IVC **Type IV late venous confluence:** Final confluence 1.5 cm from abdominal aorta **Type V rare type:** plexiform networks or aberrant drainage Right renal vein: **Type 1 additional renal vein** **Type 2 abnormal reflux :** A) single RRV and renal vein originate from the pole and drain into IVC B) single RRV drain into adjacent vein (e.g. right lumbar vein) instead IVC **Type 3 rare type:** triplication or anomalous termination	MDCT Angiography Type I 2.1% Type II 2.1 % Type III 1.7% Type IV 0.9% Type V 0.3% Type 1 18.7% Type 2 0.4% Type 3 0.1%

Table 2 Examples of Nomenclature of Renal Veins

Aljabri et al. (26)	Classified left renal vein variations into 7 types: RLRV CLRV Left sided IVC without situs inversus Left sided IVC with situs inversus Dublicate IVC Preaortic confluence of iliac veins Horseshoe kidney	Contrast-enhanced spiral CT Total: 5.65% (101/1788) RLRV 3.18% CLRV 1.62% left-sided IVC without situs inversus 0.17% left-sided IVC with situs inversus 0 duplicate IVC 0.39% preaortic confluence of iliac veins 0 horseshoe kidney 0.39%
Karaman et al. (25)	Classification retroaortic left renal vein variations: **Type I:** RLRV joining the IVC in the orthotopic position **Type II:** RLRV joining at level of L4-L5 **Type III:** CLRV **Type IV:** RLRV joining the left common iliac vein	MDCT angiography Total: 3.6% (68/1865 patients) Type I: 26 Type II: 22 Type III: 17 Type IV: 3

5.5 Diagnostic Accuracy of Different Imaging Modalities

The variance in observed frequency of renal vasculature variations is partially based on the difference in sensitivity of the different diagnostic modalities, for example Angiography, CT, CT angiography, autopsy, ultrasonography and MRI. Autopsy allows for direct anatomical observation and thus tends to yield more accurate prevalence data, although it cannot assess blood flow and is limited to deceased individuals (11). Detecting multiple renal arteries via angiography is particularly challenging when their diameter is below 2 mm. Furthermore, early branching and venous variations pose difficulties for this imaging modality. Nevertheless, according to Platt et al. angiographic imaging tends to be very accurate with RHCT (renal helical CT – with contrast) detecting 95% of the variations compared to the variations found during operations. Those 95% also highly correlate with the traditional angiographic results with an overlap of 96% of both imaging modalities. Both RHCT and CT angiography are advantageous compared to traditional angiography for patients' comfort as they are

non-invasive and do not require a catheter or additional urography (27). Further articles like Chai et al. analysed the accuracy of CT angiography finding a 95% prediction rate which is comparable to RHCT as found by Platt et al. The number of veins was even more precise with 99% success rate (28). With 3%, Kok et al. observed a slightly lower failure rate than Platt et al. in conventional angiography, using digital subtraction angiography (DSA) specifically. They compared the variations from the imaging to the intraoperative findings, where DSA failed to find variations in 3 out of 101 cases and had a sensitivity of 0.81 and a specificity of 1.00. Further, they tried to analyse whether MRI would be a suitable alternative to DSA because it is not invasive and does not expose the patient to radiation. The accuracy of the MRI was significantly lower, with it failing to predict the correct arterial anatomy in 10% of cases (sensitivity 0.61, specificity 0.98) (29). Further studies have shown that 3D CT angiography has a sensitivity of 100% compared to conventional CT, making it a suitable non-invasive alternative. It reaches an accuracy of 97.6% in renal arterial anatomy and thereby yields similar results as RHCT (30).

5.6 Ethnical differences in Frequency of Renal Vasculature Variations

In their systematic analysis Gulas et al. reported variations in the prevalence of accessory renal arteries from 4% in Malaysian population up to 61.5% in a Brazilian population. Generally, the lowest frequency was found in eastern and southern Asia with 4% to 18.4%. There was a wide variety amongst the European studies found from 11.2% of accessory renal arteries in a Greek study to 64.2% in a Bosnian study. The results of the Bosnian population also varied as one study reported a prevalence of 25.8%, while another one reported 64.2%, though the latter was focussed on the variations in fetuses which were significantly higher across populations. For instance, also in the Polish population the frequency of accessory renal arteries is higher in fetuses (21.1%) than in adults (11.2%). Excluding fetal studies, frequencies across European populations ranged from 11.2% to 31.8%, as observed in a Ukrainian study. Also, Satyapal et al. analysed the differences in frequencies but rather focussed on different races amongst the South African population. They distinguished White, Africans, Indians and Coloured, which is a mixed-race category in South Africa. Within their analysis, they found significant inter-racial differences with a higher incidence in Africans with 37.1% and White with 35.5% as opposed to 17.4% and 18.5% in Indian and “Coloured” population. For all populations data were collected via post-mortem autopsy and through clinical analysis of angiograms (11,16).

In contrast to statistically relevant differences that could be found amongst renal arterial variations within different ethnic groups, there was no relationship found with venous variations. Valenzuela Fuenzalida et al. performed a meta-analysis including 33790 patients with 72.41% being European,

7.22% Asian population, 15.1% North American, 2.07% South American and 3.19% African. From the data they collected, they concluded that there is no indication of association between ethnicity or race and the frequency of renal variations, though the analysis was based on data mostly collected from Europeans (31).

5.7 Clinical Relevance

Renal vein variations are common and of especial clinical relevance. Specifically, the retroaortic left renal vein as well as the circumaortic left renal vein can be compressed because of their anatomical position between the aorta and the spinal column. Equally, compression of the left renal vein may also occur between the aorta and the superior mesenteric artery. This phenomenon is called nutcracker syndrome/left renal vein entrapment syndrome and is discussed further in the subsequent section. These variations also increase the chance of urological symptoms including hematuria, flank pain, abdominal pain and left-sided varicocele. The venous drainage impairments that can be caused by renal vein variations, can also be associated with pelvic congestion syndrome that presents with symptoms like dysmenorrhea, dyspareunia or chronic pelvic pain. Further, autonomic symptoms like fatigue, tachycardia and orthostatic intolerance are possible but rather rare. In case of surgery or interventions, recognizing renal vein variations is important. For instance, in case of renal transplantation, which is described in more detail below, venous anastomoses should be selected correctly. Further, in adrenal surgery it should be paid attention to the frequent possibility of the adrenal vein draining into the left renal vein (25,31).

Equally to renal veins, renal arteries hold clinical significance. For instance, early branching as well as multiple renal arteries affect the surgical plan during operations like kidney transplantation and renal denervation. During kidney transplantation multiple renal arteries increase the risk ischemic injury due to longer operation time and injury to the additional renal artery (32). During catheter-based denervation early branching as well as small caliber additional arteries are a contraindication for the procedure because of injury risk and effectiveness (33,34). Further studies suggest that additional renal arteries might play a role in the pathophysiology of hypertension through the renin-angiotensin-aldosterone system (35). It can also cause hypertension by extrinsic compression of the ureteropelvic junction which is rare but surgically reversible. Additionally, additional arteries might influence the endovascular repair of aortic aneurysm. Inferior polar arteries might also be an etiological factor in hydronephrosis. Despite advances in surgical techniques, variations in renal arteries remain clinically relevant and should be considered in medical practice (36).

5.7.1 Catheter-based Renal Denervation

Catheter-based renal denervation is an important approach to treat resistant hypertension in patients. The European Society of Cardiology (ESC) defines resistant hypertension as having a blood pressure above goal (>140/90) despite being under the influence of three or more blood pressure lowering drugs. These drugs need to be of different classes, one of them must be a diuretic and they all have to be administered at their maximally tolerated doses. It is estimated that the prevalence of resistant hypertension is at about 10% (33,37).

The aim of catheter-based renal denervation as highlighted in the ESC guidelines (33) is to interrupt the afferent and efferent sympathetic nerves in the adventitia and perivascular tissue of the renal arteries. It is attractive for patients with suboptimal medication adherence, but can also be performed based on patient preference after a shared risk-benefit discussion and multidisciplinary assessment. It is not recommended as a first-line intervention for hypertension. While trials suggest a blood pressure lowering effect of renal denervation for 3-10 years, the effect is modest (decrease in 6 mmHg), especially considering the invasive nature of the intervention. Therefore many patients still require further blood pressure lowering drugs afterwards (33).

Due to its irreversible nature and high cost, the initial circumstances of each patient need to be carefully evaluated. Firstly, the penetration depth of sympathetic nerves around the renal arteries varies. Therefore, performing renal denervation in patients with deeper penetration can carry the risk of injuring the tunica intima of the artery (34).
Secondly, the procedure can only be done on the renal arteries of a bigger diameter as additional smaller arteries (<3 mm) may not achieve effective denervation and have greater risk of vascular injury. Multiple renal arteries are common similarly to early branching which is also an contraindication for renal denervation (16,33).

5.7.2 Nutcracker Syndrome (NCS)/Left Renal Vein Entrapment Syndrome

One important clinical syndrome that is associated with renal vein anatomy is nutcracker syndrome which can cause renal venous hypertension and therefore causes associated symptoms most commonly hematuria as well as flank and abdominal pain. It is caused by the compression of the left renal vein either anteriorly from the superior mesenteric artery or posteriorly between the aorta and the vertebrae (in case of retroaortic/circumaortic left renal vein). A right-sided NCS is rare and mainly present during pregnancy or due to the presence of vascular anomalies. The diagnosis of NCS is based on the presence of clinical symptoms without which it should be called nutcracker phenomenon, also known as left renal vein entrapment syndrome. Typical renal symptoms include hematuria, orthostatic

proteinuria and flank pain while urological symptoms are abdominal pain, varicocele, dyspareunia, dysmenorrhea, fatigue and orthostatic intolerance (38). Those symptoms are caused by the impaired venous drainage that the compression of the left renal vein is causing. It thereby is forcing the blood to flow through alternative collateral pathways, for instance gonadal, lumbar, uretric, capsular and adrenal veins, which can rupture and then cause hematuria (39,40). The proteinuria itself is caused by an increased filtration pressure in the renal capillaries through the venous hypertension. Varicocele is based on the congestion of the gonadal vein while pelvic congestion syndrome is a symptomatic complex present in females. If the symptoms are severe, surgical treatment becomes necessary including renal vein transposition and endovascular stenting (38). It is important to recognize left renal vein entrapment as the collateral veins may become engorged, which means they are dilated and filled with excess blood because of the increased venous pressure. This then can lead to uncontrolled hemorrhage during retroperitoneal surgeries, as the vessels become more fragile. Further, there is a risk of ligation if surgeons are not aware of the renal vein anatomy, especially during vascular surgery of the aorta and inferior vena cava (25). Another challenge for retroaortic left renal vein or NCS is adrenal vein sampling used for primary aldosteronism diagnosis where the collateral pathways can lead to misinterpretation of the hormones (40). Therefore, preoperative imaging like Multidetector computed tomography or magnetic resonance angiography are essential for preoperative assessment (25).

5.7.3 Renal Atrophy

Kidney atrophy is defined as a unilateral or bilateral shrinking of the kidney due to a loss of nephrons (41). Congenital anomalies are usually excluded from this definition (42). It is generally caused by damage to kidney tissue from different sources like chronic kidney disease, inflammation and high blood pressure. Histopathological analysis by Cumming and Schroeder revealed fibrosis in many instances (42,43), likely caused by inflammation, which is why the term “nephrofibrosis” was proposed by the authors.

High blood pressure in the kidney can have several causes. Davran et al observed a higher prevalence of atrophy in the left kidney and listed a number of reasons mainly relating to higher blood pressure in the left kidney. These are mainly anatomical reasons, e.g. higher arterial blood pressure due to the shorter distance to the heart and possible obstruction of the left renal vein as observed in nutcracker syndrome and patients with splenomegaly (41). Other factors that contribute to increased internal pressure in the kidney are vascular issues like arteriosclerosis, and obstructions in the upper urinary tract like kidney stones. Especially the presence of multiple stones and long duration of the disease (> 12 months) increased the risk of kidney atrophy (44).

A study by Xiangrui et al demonstrates that kidney atrophy can even occur in patients after percutaneous nephrolithotomy, either due to high perfusion pressure during the operation or due to hydronephrosis and pyonephrosis after the operation (44). All these conditions are marked by increased pressure in the kidney, either from swelling or perfusion, which causes stress for the endothelium and can cause long-term thickening of the blood vessel walls.

For diagnosis, several options exist. Blood tests, analysis of renin secretion and urinalysis can all be helpful, but to properly identify atrophy in the kidney, imaging techniques are preferrable, as they can be used to compare the size and shape of the kidneys (45,46). Ultrasonography is a cheap and reliable method (41), but normally only shows 2D images. Magnetic resonance imaging (MRI) and X-ray computer tomography (CT) are more advantageous in that regard, as these methods simplify determination of both dimensions and volume of the kidneys. However, they are more expensive and CT potentially needs nephrotoxic contrast agents (45).

Treatment of kidney atrophy is difficult, as most of the time the condition is irreversible. In some cases, medical treatment may be sufficient (47). An observational retrospective study conducted by Marboeuf et al at the Lille Hospital Center grouped patients based on renal clearance and renin hypersecretion. The authors found that for patients where the atrophic kidney still accounted for more than 10% of total renal function endovascular revascularization proved effective. When renal function of the atrophic kidney was too low and the atrophic kidney showed hypersecretion of renin compared to the contralateral kidney, nephrectomy was performed, which resulted in 40 mmHg reduction of systolic blood pressure (47).

In severe cases, especially for bilateral atrophy, kidney transplantation is necessary, as the intervention has shown lower mortality and higher quality of life improvements for patients than life-long dialysis (48).

5.7.4 Kidney Transplant

During a kidney transplant, a healthy kidney from either a deceased or a living donor, is transplanted to the patient, preferably into the iliac fossa connecting to the external or internal iliac artery and vein while the ureter is anastomosed to the bladder (6). An example of how that can be performed can be seen in case number 4 in the results section. Renal vasculature can influence the duration, success and complication rate of kidney transplantation. If there are multiple renal arteries present, it increases the risk of ischemic injury because of its challenges on their reconstruction as it increases warm and cold ischemic time significantly ($p<0.05$) extends the operative time from 115 (+/- 15.4) minutes with a solitary renal artery to 135 (+/- 23.0) minutes (21,32). This is also based on the fact that ligating one of the renal arteries may leads to segmental ischemia of the kidney, as there are no anastomoses

between them which compromises the long term graft function (49). Further, the presence of early branching can be challenging as the renal artery incision should be done 1.5-2 cm distal from the aorta. Also, multiple renal veins play an important role as they may require multiple anastomoses and thereby increase the risk of venous thrombosis. The retroaortic renal vein specifically often has lumbar retroperitoneal tributaries that are at risk to be injured during operations. Vascular variations are not a contraindication for kidney transplantation but are transplanted readily and show no significant differences (95.4% vs 91.2%) in graft survival (32). Though having more than 2 arteries increase the risk of delayed graft function by 1.2 while the risk with two arteries is not significantly increased compared to a single artery. With 8.3% vs 5.9% the occurrence of renal artery stenosis in patients with multiple renal arteries was statistically significant. Nevertheless, acute rejection and renal artery thrombosis, hematoma as well as urological complications were not significantly different (50). All in all, it is important for transplant surgeons to be aware of the variations to prevents complications, considering that fifty percent of living kidney donors have either early divisions or multiple renal arteries (21).

5.7.5 Renal Agenesis

Renal agenesis is a term used to describe the congenital absence of one or both kidneys. The development of the functioning kidneys starts, as described in the embryology section, with metanephros during the 5th week of gestation. There the ureteric bud arises from the metanephric duct and failure of this ureteric bud outgrowth is one of the three main pathways that can lead to renal agenesis. Another one is during invasion of the mesenchyme from the ureteric bud which is the following step after the bud outgrowth. Further, through reciprocal induction of the metanephric mesenchyme with ureteric bud kidney formation progresses. Failure of this signaling pathway, including GDNF/RET, PAX2, WT1, and WNT4 leads to renal agenesis or dysplasia. All in all, 3 pathways are known to be a possible cause of renal agenesis including failure of bud outgrowth, invasion of mesenchyme or of the signaling pathway from reciprocal induction. Further, teratogenic influences like maternal diabetes and drug exposure might lead to renal agenesis. Usually, unilateral renal agenesis is asymptomatic and might be detected incidentally. Nevertheless, there is an increased risk of proteinuria, hypertension and renal insufficiency. There is also an association of renal agenesis with certain syndromes like Kallman's syndrome or trisomy 21. Frequency of unilateral renal agenesis is approximately 1 in 1000 live births according to the Society for Maternal-Fetal Medicine (51). This is significantly higher than bilateral renal agenesis which is not compatible with life and occurs in 1 in 3000-4000 live births (9,51,52).

6 Methods

To conduct the study presented here, a study on cadaveric samples was conducted. The cadavers were donated to Vilnius University Faculty of Medicine and embalmed in 10% formalin solution within the facilities. In total 13 cadavers were dissected of which three only displayed one kidney resulting in a total of 23 kidneys analysed. The cadavers were dissected over a period of 14 months and continuously analysed.

Autopsy was used as a analysing method as its direct observation leads to more accurate results than with indirect analysing methods through imaging (11). Different technologies like CT, CT angiography, RHCT, DSA and MRI lead to differently accurate results and are indicated in varying circumstances. A more specific description of their distinctions can be found in “Diagnostic Accuracy of Different Imaging Modalities”.

Regarding the classification of renal artery variations, there are multiple classifications used some of which are explained in table 1 “Examples of Nomenclature of Renal Arteries”. The classification used is based on the one from Sampaio and Passos originally proposed in 1992. It was chosen because it’s a widely known, used and detailed classification that includes all main variations except from perihilar branching which was partly excluded only including the branches supplying the poles called extra-hilar branch by Sampaio and Passos. This was further classified below (1).

In the article of Sampaio and Passo the renal artery that originates from the Aorta and supplies the hilum is called hilar artery. This term is logical as it clearly describes its path. In figure 1A the hilar artery is shown, representing the standard anatomy without any variation or branching (1).

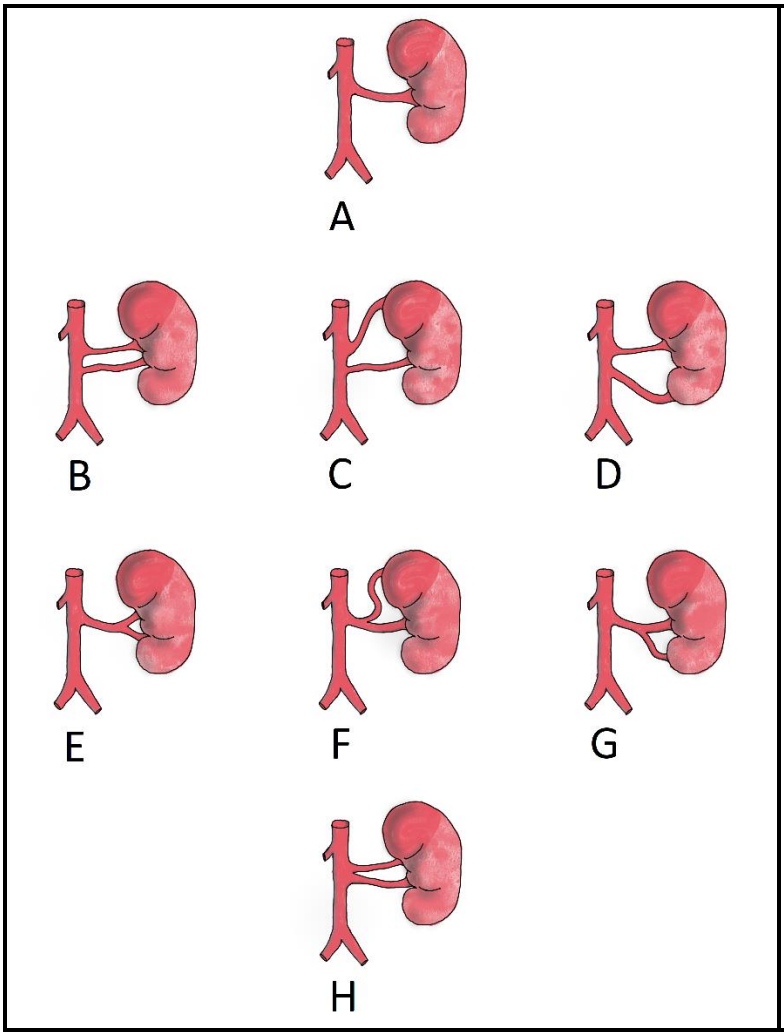
If more than one hilar artery is present, the term multiple arteries is used. Each artery that supplies the hilum from the aorta is still called hilar artery. In contrast to Negromonte et al. (15) it was chosen not to include "dominant" and "accessory". They argued that it can adequately describe which renal artery supplies the larger portion of the parenchyma. Nevertheless, here the approach from Sampaio and Passos (1) was chosen because calling them „dominant“ or „accessory“ can be misleading as it implies that the accessory one would not be necessary. Though in fact none of the multiple renal arteries should be ligated as it would lead to ischemia and necrosis regardless of diameter, because they are corresponding to the segmental branches of the kidney. For the same reason the terms „extra“ and „aberrant“ were excluded (1,15).

Further, Sampaio and Passos (1) call the arteries supplying the poles of the kidney from the aorta, superior and inferior polar artery respectively. The terms inferior and superior were preferred to the term upper and lower polar like in the publication of Cases et al. (18) who called them aortic upper

or lower polar arteries and Budhiraja et al. (20) naming them upper or lower polar supernumerary renal artery. This preference is based on the fact that inferior and superior are the standard topographical description in anatomy. Nevertheless, Cases et al. (18) specified their aortic origin by calling them aortic upper or lower polar artery which was adopted to this terminology as it makes the classification more clear. Therefore, they are called aortic superior or inferior polar artery respectively (figures 1C and 1D) (1,18,20).

Close to the hilum the renal artery divides into anterior and posterior branch which are called presegmental arteries. Altogether this is called perihilar, prehilar or extrahilar branching (3,13,53). For the purpose of this thesis the term perihilar branching was chosen, as it more accurately describes where the renal artery branches, being within the vicinity of the renal hilum. This terminology was not included in Sampaio and Passos, but was chosen to be included to reflect its importance. Kang et al. (53) further classified the perihilar branching into three types from no segmental artery to two segmental arteries which also contain further subcategories. Nevertheless, for simplicity reasons the further categories of Kang et al. are excluded. If the renal artery split within 1.5 cm of the origin at the aorta, the term early branching was chosen (13). This distinction between perihilar and early branching is necessary because of its surgical importance, as early branching can create particular challenges for kidney transplantation further described in the corresponding chapter (13). Another term for early branching is also precocious bifurcation which was excluded because the term bifurcation implies that the structure would divide into two structures which in some rare cases can be more than that (1).

All in all, through this the following classification was chosen. Arteries that originate at the aorta and then supply the kidney at the hilum are called hilar arteries (figure 1A) and if there is more than one the term multiple (figure 1B) was utilized. In case of a renal artery originating from the aorta and supplying one of the poles of the kidney, they are named aortic superior or inferior polar arteries reflected in figures 1C and 1D. If they originate form the renal artery, they are labeled as perihilar superior (figure 1F) or inferior polar arteries (figure 1G). Generally, perihilar branching is branching close to the hilum, if the artery supplies the hilum its called perihilar artery (figure 1E). This in itself is not considered a true variation, because it stems from an early splitting of the pre-segmental and segmental branches (53). Finally, branching within 1.5 cm of the aorta is early branching, seen in figure 1H.



A Hilar artery
B Multiple hilar arteries (Hilar artery 1-5)
C Aortic superior polar artery
D Aortic inferior polar artery
E Perihilar branching
F Perihilar superior polar artery
G Perihilar inferior polar artery
H Early branching

Figure 1 Vasculature variations of the renal arteries

There are multiple classifications for renal vein variations reflected in table 2 " Examples of Nomenclature of Renal Veins". For the renal veins the classification that is used as a basis is from Zhu et al. because of its detailed categorization and its wide usage (24).

For the renal vein variations, there are differences between right and left renal vein variations. In the meta-analysis of Hostiuc et al. (2) they do not specify whether it's on the right or left side and use a simplified classification of the diverse variations. Specifically, they distinguish circumaortic, retroaortic and multiple/double renal vein, also seen in table 2 "Examples of Nomenclature of Renal Veins". Most authors distinguish circumaortic and retroaortic left renal vein as variations including Zhu et al. (24). Therefore, these terms were adopted into the classification, also because of their precise description of the anatomical topography. Circumaortic as well as retroaortic renal vein variations are usually on the left renal vein as the vena cava is on the right side of the aorta. This also causes the left renal vein to be longer. Therefore many classifications like the once from Zhu et al. (24) and Valenzuela Fuenzalida et al. (31) distinguish variations on the right and left renal vein. This differentiation is also used in this classification reflected in figure 2 and 3. Some authors, for instance

Aljabari et al. (26) even decided to focus on the left renal vein in their classification thereby including more rare variations like left sided IVC or duplicated IVC. Karaman et al (25) also focused on left renal variations, specifically only analysing the retroaortic left renal vein variations which included circumaortic left renal vein as type III. In their classification they focus on where the veins drain into for instance the IVC in orthotopic position or in type IV the left common iliac vein. Neither the classification of Aljabari et al. (26) nor the one from Karaman et al. (25) is used with their detail as many of those variations are rather rare and complicate the categorization. Also, the tributaries of the renal vein like upper primary or posterior primary explained by Satyapal et al. (54)were excluded. In comparison to Zhu et al. (24) there is an additional type for right and left renal veins without variations each being type 1 and I respectively. Otherwise, the right renal vein is classified in the same way as Zhu et al. (24) did. The variation of additional renal veins is not only used for the right renal vein like in Zhu et al. (24) but was rather adopted to both right and left renal vein, as it appears on both sides. The term additional is chosen as in comparison to the renal arteries, renal veins are within their arcuate and interlobar veins interconnected which therefore allows ligation (6). Further, circumaortic renal vein is not further divided into subcategories. The two types of abnormal reflux on the left renal vein by Zhu et al. (24) are included reflected in type V and VI.

To summarize, the right renal vein is categorized into four types with the right renal vein labeled with 1, and additional renal vein with 2 which arise from the hilum and drain into the IVC. The 3rd variation is abnormal reflux and includes additionally to the right renal vein, a renal vein originating from the pole and draining into the IVC or when the RRV drains in one of the adjacent veins instead or in addition to the IVC. Finally, with in category 4 all variants that are not included before are joined together including triplications and anomalous terminations.

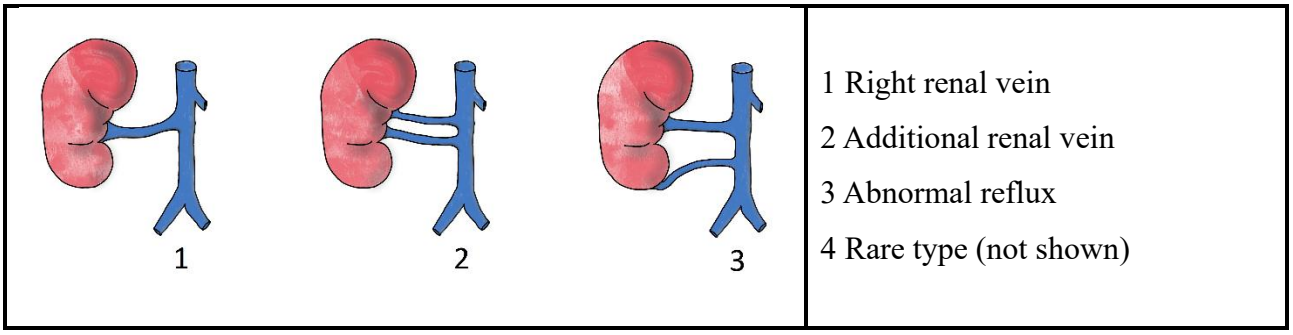
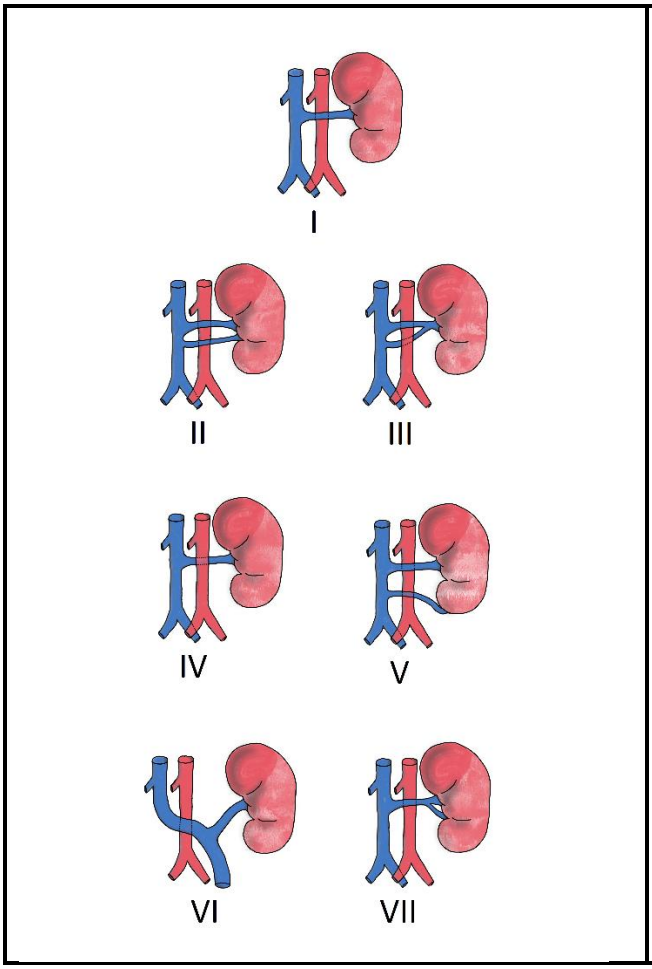


Figure 2 Vasculature variations of the right renal vein

In comparison to the right renal vein, the left renal vein has eight types. Nevertheless, the incidence of right renal variations is significantly higher (19.2%) than that of the left (7.1%) (24). A vein that is complementary to the left renal vein is called additional renal vein like in the right renal vein. The abnormal reflux is also a variation on the left side, though there are two types distinguished with type

A (figure 3V) being an additional artery draining from the poles of the kidney and type B (figure 3VI) being drainage from the left sided IVC, vena hemiazygos or left limb of double IVC. This distinction was taken from Zhu et al. (24) where this is called type IIIA and IIIB illustrated in table 2 “Examples of Nomenclature of Renal Veins”. Other than that, circumaortic, retroaortic and rare type of left renal vein were distinguished. Further, the variation figure 3VII being late venous confluence is used and defined as a final confluence within 1.5 cm of the aorta laterally (24).



I Left renal vein
II Additional renal vein
III Circumaortic left renal vein
IV Retroaortic left renal vein
V Abnormal reflux type A
VI Abnormal reflux type B
VII Late venous confluence
VIII Rare type (not shown)

Figure 3 Vasculature variations of the left renal vein

7 Results and Discussion

Following the example of Garcia-Barrios et al. (55) the table below was created illustrating the cases of renal vasculature anatomy present at the cadaver dissection performed on the premises of Vilnius University Faculty of Medicine. The images corresponding to each of the cases can be found in Annex 1 that also labels the structures shown. A summary of their prevalences is shown in table 4 with the most frequent variations were perihilar and early branching of the renal arteries.

Table 3 Vasculature Findings of Dissection of Bodies donated to Vilnius University

Case number	Arterial anatomy		Venous anatomy	
	Right	**Left**	**Right**	**Left**
1	A) Hilar artery H) Early branching of hilar artery	A) Hilar artery	1) Right renal vein	I) Left renal vein
2	A) Hilar artery E) Perihilar branching	A) Hilar artery	1) Right renal vein	I) Left renal vein III) circumaortic left renal vein
3	A) Hilar artery E) Perihilar branching F) Perihilar superior polar artery	A) Hilar artery C) Aortic superior polar artery E) Perihilar branching	1) Right renal vein	I) Left renal vein VI) abnormal reflux type B (vena hemiazygos)
4	A) Hilar artery C) Aortic superior polar artery H) Early branching of Hilar artery	A) Hilar artery H) Early branching of Hilar artery	1) Right renal vein	I) Left renal vein
	Kidney transplant right iliac fossa Anastomosis with external iliac artery and vein			
5	A) Hilar artery C) Aortic superior polar artery	/ no kidney	1) Right renal vein	/ no kidney
6	A) Hilar artery C) Aortic superior polar artery F) Perihilar branching of hilar and aortic superior polar artery	A) Hilar artery H) Early branching of Hilar artery	1) Right renal vein 2) Additional renal vein	I) Left renal vein II) Additional renal vein
7	A) Hilar artery	A) Hilar artery	1) Right renal vein	I) Left renal vein

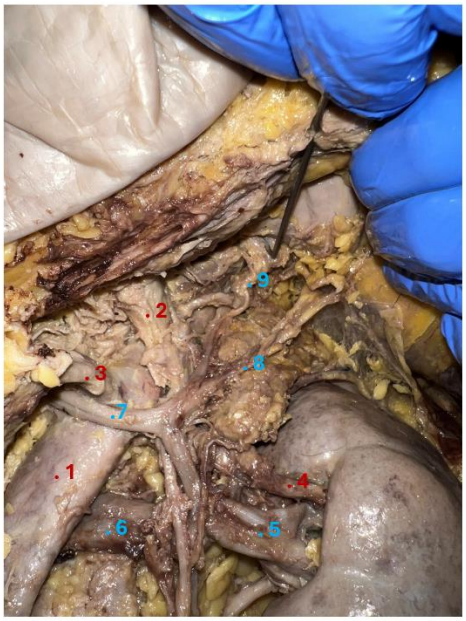
Table 3 Vasculature Findings of Dissection of Bodies donated to Vilnius University

	E) Perihilar branching F) Perihilar superior polar artery	D) Aortic inferior polar artery F) Perihilar superior polar artery		
8	A) Hilar artery H) Early branching	A) Hilar artery E) Perihilar branching	1) Right renal vein 2) Additional renal vein	I) Left renal vein
9	/ No kidney	A) Hilar artery F) Perihilar superior polar artery H) Early branching	/ No kidney	I) Left renal vein V) Abnormal reflux Type A
10	/ No kidney	A) Hilar artery	/ No kidney	I) Left renal vein IV) Retroaortic renal vein VII) late venous confluence
11	A) Hilar artery C) Aortic superior polar artery E) Perihilar branching	A) Hilar artery	1) Right renal vein	I) Left renal vein
12	A) Hilar artery F) Perihilar superior polar artery	A) Hilar artery	1) Right renal vein	I) Left renal vein
13	A) Hilar artery B) Multiple hilar arteries (double) E) Perihilar branching	A) Hilar artery E) Perihilar branching	1) Right renal vein	I) Left renal vein

Table 3 Vasculature Findings of Dissection of Bodies donated to Vilnius University

	F) Perihilar superior polar artery H) Early branching			

Retroaortic and circumaortic left renal veins are important to recognize because of their clinical implications, especially the nutcracker syndrome described further in the associated chapter. An exemplary image from the dissection can be seen in figure 4 “Case 2 – Left renal vasculature with circumaortic left renal vein”. In this figure, a circumaortic left renal vein can be seen, represented with the numbers 6 and 7. Additionally, the left adrenal vein 8 is draining into the left renal vein.



1. Aorta
2. Celiac trunk
3. Superior mesenteric artery
4. Hilar artery

Circumaortic renal vein:

5. Common trunk of left renal vein
6. Left renal vein (posterior to Aorta abdominalis)
7. Left renal vein (anterior to Aorta abdominalis)
8. Left adrenal vein
9. Left gastric vein

Figure 4 Case 2 – Left renal vasculature with circumaortic left renal vein

In figure 5, there is a representative image of early branching which has a high prevalence in the sample with 30.4% in comparison to other studies, which can be seen in table 5 “Prevalence of Renal Artery Variations across Studies”. In the image it is visible that the renal artery has a common origin at the aorta and then splits in two renal arteries within 1.5 cm which meet the definition found in the methodology. One of those early branches supplies the pole of the kidney which is why it was called perihilar superior polar artery. The term aortic superior polar artery would not apply because it is not a separate artery at the aorta. In comparison to that, in figure 6 which shows the left renal vasculature of case 3, an aortic superior polar artery is shown. Additionally, in case 9 there was an abnormal reflux type A, which is drainage from one of the poles of the kidney. This variant is labeled with the number

6 and was only present once within the sample. This creates a prevalence of 8.3% which is comparably high but could be due to the small sample size. Similarly, the abnormal reflux type B was present once shown in figure 6. There vena hemiazygos drainage is present.

Figure 5 Case 9 – Left kidney vasculature with abnormal reflux type A and early branching.

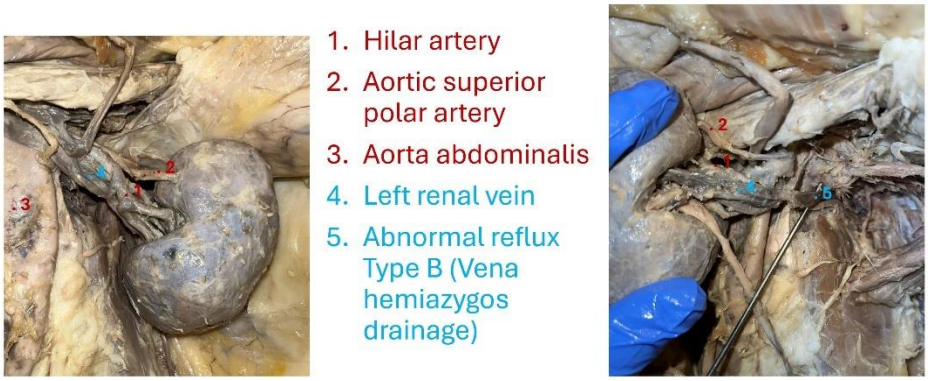


Figure 6 Case 3 – Left renal vasculature with aortic superior polar artery and abnormal reflux from vena hemiazygos.

Figure 7 represents a special case found during the dissection. Here both kidneys were atrophied, and a kidney transplant was present at the right iliac fossa. Their anastomoses can be seen in the upper picture of the figure. The location at the right iliac fossa is typical for kidney transplantation. The transplanted kidney seems to only have one renal artery which is preferably for kidney transplantation as it decreases cold ischemia time (21,32).

The renal atrophy can be due to multiple causes, for instance chronic kidney disease and inflammation. This is explained in more detail in the respective chapter of the literature review. The specific cause of the atrophy in this case is not known to the author.

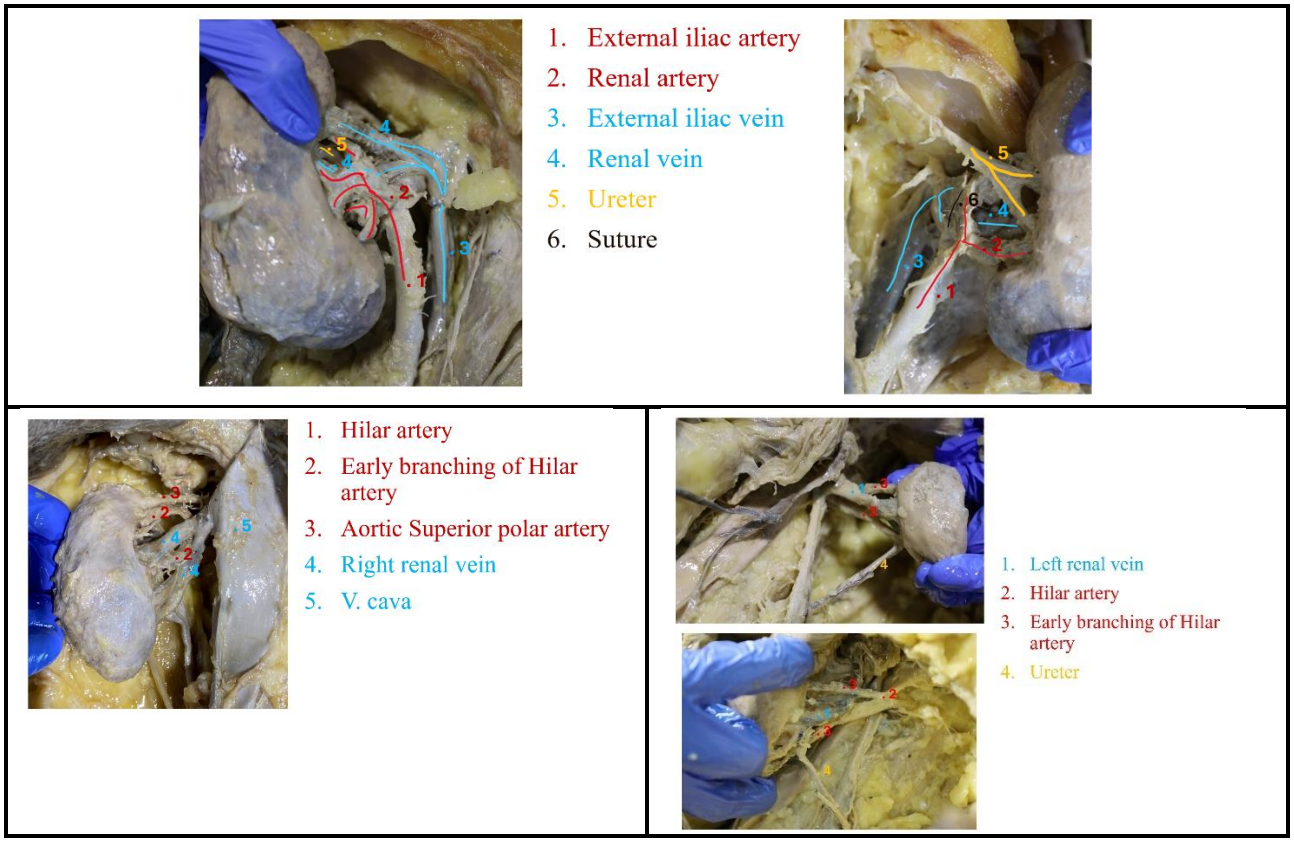


Figure 7 Case 4 Example of Kidney transplant in right iliac fossa and corresponding atrophied kidneys

In total, there were 3 cases where no kidney could be found, specifically in case 5 where the left kidney was missing and in case 9 and 10 where the right kidneys were not present. In case 5, there is a left renal vein present as shown below. Therefore, it can be concluded that this is not a case of renal agenesis but rather there must be another iatrogenic cause. In comparison to that, in case 9 and 10 there was no renal vasculature found. This could be because of renal agenesis or other for instance iatrogenic causes. As the incidence of renal agenesis (further described in the associated chapter) is 1 in 1000 (51), a prevalence of 2 in 26 would be extremely high which suggests that there might be an iatrogenic cause possible.

1. Left renal artery
2. Aorta abdominalis
3. Left renal vein

1. Portal vein
2. Left renal vein

• Anatomical findings

- No right kidney present
- No right renal artery or vein

1. Duodenum
2. Portal vein

• Anatomical findings

- No right kidney present
- No right renal vein or artery

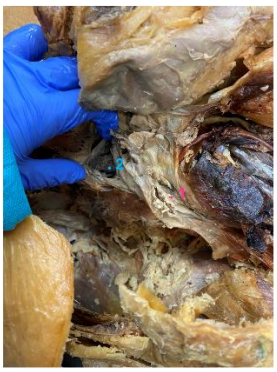


Figure 8 Case 5, Case 9 and Case 10 Examples of Cases without kidneys

Table 4, which can be seen below, shows the prevalence of renal vasculature variations including all 13 cases shown in table 3 “Vasculature Findings of Dissection of Bodies donated to Vilnius University”. The number of kidneys is only 23 rather than 26 because as previously described three kidneys were not present upon dissection. The division into arterial variations and right and left venal variations was done according to the classification of renal vasculature variations found in the methodology. Every kidney had a hilar artery, a right renal vein and a left renal vein which is why they are present within 100% of all kidneys dissected.

Within the arterial variations, there was one double hilar artery resulting in a frequency of 4.3%. Aortic superior polar arteries were more frequent (five cases/21.7%) than aortic inferior polar arteries (one case/4.3%). Similarly, perihilar superior polar artery, with six cases (26%), had a greater incidence than the left one which was not found within the samples. The most common variation found was perihilar branching with nine cases and a prevalence 39.1%. Also, early branching had a high frequency of 30.4%, which is particularly interesting for its clinical relevance in kidney transplantation explained further in corresponding chapter of the literature review.

For the right renal vein, there were only three variations classified: additional renal vein, abnormal reflux and rare type of which only the additional renal vein was present in 18.1% of cases. On the other hand, the left renal vein had one of each variation classified except for the rare type.

Table 4 Prevalence of renal vasculature variations

Total number of kidneys = 23 **Total number of cases = 13**	**Absolute number N**	**Frequency in %**
Arterial Variations		
Hilar artery	23/5/8	100%/21.7%/34.7%
Multiple hilar arteries (Hilar artery 1-5)	1	4.3%
Aortic superior polar artery	5	21.7%
Aortic inferior polar artery	1	4.3%
Perihilar branching	9	39.1%
Perihilar superior polar artery	6	26%
Perihilar inferior polar artery	0	-
Early branching	7	30.4%
Right Renal Vein Variations		
Right renal vein	11/9	100%/81.8%
Additional renal vein	2	18.2%
Abnormal reflux	0	-
Rare type	0	-
Left Renal Vein Variations		
Left renal vein	12/6	100%/50%
Additional renal vein	1	8.3%
Circumaortic left renal vein	1	8.3%
Retroaortic left renal vein	1	8.3%
Abnormal reflux type A	1	8.3%

Table 4 Prevalence of renal vasculature variations

Abnormal reflux type B	1	8.3%
Late venous confluence	1	8.3%
Rare type	0	-

In the following section the renal artery variations shown in table 4 are compared to those of Sampaio and Passos (1), Budhiraja et al. (20) and Abuelnor et al. (17). Their nomenclatures are explained further in table 1 “Examples of Nomenclature of Renal Arteries”. There are 5 cases (21.7%) with no variations in the renal arteries, meaning that only one hilar artery was present without any branching. As perihilar branching is a normal variant and their existence is not collected in many papers including the one of Sampaio and Passos (1) (see table 1), it can be assumed that the actual case number without variation is 8 being 34.7%.This number is comparably lower (meaning variations were more frequent) than in the paper of Sampaio and Passos (1) which found a normal anatomy in 55.3% of cases. In the systematic review of Abuelnor et al. (17) the rate of hilar artery was even higher, represented with 81.05% of cases. However, another cadaver study from Budhiraja et al. (20) showed a prevalence of 40.5% which is similar to the percentage of 34.7% presented here. Further comparison of variations with Sampaio and Passos (1) shows that having two hilar arteries was present in 4.3% of cases compared to their study showing 7.9%. All variations with more than two hilar arteries were not found in this study and were also rare in the paper of Sampaio and Passos (1), for instance three hilar arteries were present in 1.9% of cases. Budhiraja et al. (20) and Abuelnor et al. (17) did not specify the specific number of multiple renal arteries but account their variation with 21.6% and 11.97% respectively. Though it can be assumed that they have included early branching in their definition of multiple renal arteries which would explain the higher rates. In this study, the number of early branching is with 30.4% compared to a much lower frequency by Sampaio and Passos (1) with 2.6% and Budhiraja et al. (20) with 8.1%. A common variation is aortic superior polar artery with 21.7% and 8.7% (1.9% with further variations) in the classification of Sampaio and Passos (1). The study of Budhiraja et al. (20) shows intermediate results with 14.9%. The systematic review of Abuelnor et al. (17) cannot be compared as they do not distinguish between aortic and hilar origin of the polar arteries. Though they analyzed a prevalence of 6.46% and 6.24% for superior and inferior polar arteries respectively, which is lower than the other cadaveric studies described in table 1. Compared to the aortic superior polar artery, the inferior one is all other three papers less frequent with a range from 10.3% (20) to 4.3% in the cadaveric study from Vilnius University described here. Sampaio and Passos (1) found intermediate prevalences with a total of 6.8% of which 1.5% are having further variations. The most frequent variation in Sampaio and Passos (1) paper is perihilar superior polar branch which they call

superior pole extra-hilar branch present in 17.7% of cases in total of which 3.4% had further variations. With 26% prevalence the perihilar superior polar branch was also frequent in the data presented here. In the cadaveric study of Budhiraja et al. (20), the frequency is with 3.7% comparably low. Finally, dissections of cadaveric specimens from Vilnius University revealed no cases of perihilar inferior polar arteries. This contrasts modestly with the 6.4% prevalence (1) reported in the foundational study, some of which occurred alongside additional vascular variants. Though Budhiraja et al. (20) found comparably low prevalences with 1.4%.

Table 5 Prevalence of Renal Artery Variations across Studies

	Anatomical Variation	**Present Study (Vilnius University)**	**Sampaio and Passos (1)**	**Budhiraja et al. (20)**	**Abuelnor et al. (17)**
1	Single Hilar Artery	34.7%	55.3%	40.5%	81.05%
2	Multiple hilar arteries	4.3%	9.8%	21.6%	11.97%
3	Aortic superior polar artery	21.7%	8.7% (6.8%+1.9% with further variations)	14.9%	6.46%
4	Perihilar superior polar artery	26%	17.7% (14.3%+ 3.4% with further variations)	3.7%	
5	Aortic inferior polar artery	4.3%	6.8% (5.3%+1.5% with further variations)	10.3%	6.24%
6	Perihilar inferior polar artery	0%	6.4%	1.4%	
7	Early branching	30.4%	2.6%	8.1%	-

For right renal variation, in table 2 “Examples of Nomenclature of Renal Veins”, there are two classifications specifically from Hostiuc et al. (2) and Zhu et al. (24) that include the right renal vein variations. The results can be directly compared to the ones from Zhu et al. (24) as the types of variations are identical. There additional renal veins were present in 18.7% of cases which is almost identical to the 18.1% found in the samples here shown in table 4 “Prevalence of renal vasculature

variations". Abnormal reflux and rare type were not present here and had a small prevalence of 0.4% and 0.1% respectively in the publication of Zhu et al. (24). A direct comparison with the meta analysis of Hostiuc et al. (2) is of higher difficulty as there was no distinction between right and left renal vein. Though their prevalence of multiple renal veins should approximately reflect the one of additional renal vein where it has a similar prevalence being 16.7%.

Table 6 Prevalence of Right Renal Vein Variations across Studies

	Right Renal Vein Variations	**Present Study (Vilnius University)**	**Zhu et al. (24)**	**Hostiuc et al. (2)**
1	Additional renal vein	18.1%	18.7%	16.7%*
2	Abnormal reflux	0%	0.4%	-
3	Rare type	0%	0.1%	-

* Number of additional renal veins for right and left renal vein

The left renal vein variations are also described in table 2 "Examples of Nomenclature of Renal Veins", though there are more classifications described. In addition to the once from Hostiuc et al. (2) and Zhu et al. (24) there are two more classifications describing left renal vein variations, specifically Aljabri et al. (26) and Karaman et al. (25). In comparison to the right renal variations, there was only a prevalence of one case (8.3%) of each variation except from in the rare type which was not found at the samples from Vilnius University at all (see table 4). Though this represents a high occurrence in comparison to the other studies mentioned before. The prevalence of retroaortic left renal vein variants from 2.1% by Zhu et al. (24) to 3.18% by Aljabri et al. (26). Circumaortic left renal vein occurred in a similar frequency from 0.9% by Karaman et al. (25) to 3.5% by Hostiuc et al. (2). The variants of abnormal reflux and late venous confluence as well as the rare type were only classified by Zhu et al. represented with 1.7%, 0.9% and 0.3% respectively. These were present at a higher rate at the present study as well with abnormal reflux even having a combined prevalence of 16.6%.

Table 7 Prevalence of Left Renal Vein Variations across Studies

	Left Renal Vein Variations	**Present Study (Vilnius University)**	**Zhu et al. (24)**	**Hostiuc et al. (2)**	**Karaman et al. (25)**	**Aljabri et al. (26)**
1	Retroaortic left renal vein	8.3%	2.1%	3%	2.7%	3.18%

Table 7 Prevalence of Left Renal Vein Variations across Studies

2	Circumaortic left renal vein	8.3%	2.1%	3.5%	0.9%	1.62%
3	Abnormal reflux	16.6%	1.7%	-	-	-
4	Late venous confluence	8.3%	0.9%	-	-	-
5	Rare type	0%	0.3%	-	-	-

In table 8, there is a comparison of the renal artery variations across countries or ethnicities. Satyapal et al. (16) compared different ethnicities amongst the South African population which is described in more detail under “Ethnical differences in frequency of renal vasculature variations”. In their study they only considered those originating from the aorta as additional renal arteries. In this study the term additional artery was not used as reasoned within the methodology. Therefore, their term additional artery would include the categories multiple hilar arteries (4.3%), aortic superior polar artery (21.7%), aortic inferior polar artery (4.3%) in this study. Therefore, according to their definition, the data would conclude a prevalence of 30.3% which is similar to the 35.5% found in the White South African population and the 37.1% in Africans by Satyapal et al. (16). This was compared to the 17.4% and 18.5% of prevalence in Indian and “Coloured” population a significantly higher prevalence. As their methodology was consistent across the study, and it was not a comparison of different studies, this data is more robust compared to the data from Gulas et al. (11) who compared data from different countries and across different studies published. This also included different analysing technologies across studies. Also, it was more difficult to compare to the present data as it was not clearly indicated what they define as “accessory arteries”. Assuming that they define “accessory arteries” in a similar way than Satyapal et al. defines “additional arteries” than the frequency of 30.3% would be in the middle of the spectrum (4-61.5%) similarly to the frequency found by Vilhova et al. (56) in Ukraine. Though as 81% (30/37) of studies are ranging from 4 to 30%, the data found is rather within the upper quartile when comparing to the data set of Gulas et al. (11). This would align with the conclusion that people of white ethnicity and the Lithuanian population as such could have a higher prevalence of renal artery variations.

A comparison of renal vein vasculature of different ethnicity has not been performed, as the meta-analysis of Valenzuela Fuenzalida et al. (31) found no significance. This is further explained in the chapter “Ethnical differences in frequency of renal vasculature variations”.

Table 8 Prevalence of renal artery variations of Lithuanians compared to other ethnicities/population

Ethnicity/population	Definition	Frequency of Renal Artery Variation
Lithuanian (Present Study)	Arteries with aortic origin: multiple hilar (4.3%), aortic superior polar (21.7%), and aortic inferior polar (4.3%) arteries	30.3%
South African population by Satyapal et al. (16)		
White South Africans	Additional arteries - Includes all arteries that origin from the aorta	35.5%
Black South Africans		37.1%
Indian South Africans		17.4%
"Coloured" South Africans		18.5%

8 Limitations

Because of the small sample size of 23 dissected kidneys, only limited conclusions about the population-wide prevalence can be drawn. Further, the frequency of observed rare variations is inflated due to the small sample size.

Comparison of this study as well as across studies within the literature is challenging considering the methodological discrepancies arising from the use of different imaging-based studies (e.g. CT, MRI) versus autopsy as well as the diverse classification systems for the variations itself. These inconsistencies further increase the difficulty of comparing data from different ethnicities with one another.

While direct observation during dissection provides a high accuracy, visual dissections are prone to observer-dependent bias. To reduce this bias, clear definitions of individual variations were created.

9 Conclusion

1. This study underscores the high prevalence of renal vasculature variations, aligning with existing literature.
2. In 8 out of 23 cases (34.7%) the classical anatomy of a single hilar renal artery is displayed confirming the high rate of arterial variation. The most common variation identified was early branching with 7 out of 23 cases (30.4%).
3. Venous variations were also prominent, with standard anatomy observed in 9 out of 11 (81.8%) right renal veins and 6 out of 12 (50%) left renal veins.
4. Direct cadaveric dissection exceeds imaging-based studies in accuracy, allowing for a clear identification of the vascular structures.
5. A clear and precise classification system was applied to both arterial and venous variations, distinguishing them based on their origin and supplied region.
6. For the venous variations the classification an established classification system by Zhu et al. (24) was adopted. A distinction was made between right and left renal vein variations, with the left renal vein potentially exhibiting circumaortic or retroaortic configurations, as well as late venous confluence.
7. In contrast, the renal arterial classification incorporated terminology from several literature sources. The term “multiple arteries” is used to refer to any additional artery. To further specify their origin and supplied region the classification adopts the terms perihilar or aortic superior/inferior polar artery. A clear distinction was also made between perihilar branching and early branching due to its anatomical and surgical significance.
8. The study provides a pilot dataset on renal vascular variations within the Lithuanian population. Given the relatively small sample size, further research is needed to be able to make any definite conclusions,
9. This thesis highlights the need for a standardized classification system that ensures consistency and comprehensibility for comparison of future anatomical studies.

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11 References

1. Sampaio FJB, Passos MARF. Renal arteries: anatomic study for surgical and radiological practice. Surg Radiol Anat. 1. Juni 1992;14(2):113–7.

2. Hostiuc S, Rusu MC, Negoi I, Dorobanțu B, Grigoriu M. Anatomical variants of renal veins: A meta-analysis of prevalence. Sci Rep. 25. Juli 2019;9:10802.

3. In: Guyton and Hall textbook of medical physiology: Student consult. 12. ed. Philadelphia, Pa: Saunders, Elsevier; 2011. S. 303–7.

4. Gray H, Drake RL, Vogl W, Mitchell AWM. Gray's anatomy for students. Third edition. Philadelphia, PA: Churchill Livingstone Elsevier; 2015. 1161 S.

5. Graves FT. The anatomy of the intrarenal arteries in health and disease. J Br Surg. 1. Mai 1956;43(182):605–16.

6. Arévalo Pérez J, Gragera Torres F, Marín Toribio A, Koren Fernández L, Hayoun C, Daimiel Naranjo I. Angio CT assessment of anatomical variants in renal vasculature: its importance in the living donor. Insights Imaging. 26. Januar 2013;4(2):199–211.

7. El-Galley RES, Keane TE. EMBRYOLOGY, ANATOMY, AND SURGICAL APPLICATIONS OF THE KIDNEY AND URETER. Surg Clin North Am. 1. Februar 2000;80(1):381–401.

8. Rehman S, Ahmed D. Embryology, Kidney, Bladder, and Ureter. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 [zitiert 8. Februar 2025]. Verfügbar unter: http://www.ncbi.nlm.nih.gov/books/NBK547747/

9. Smyth IM, Cullen-McEwen LA, Caruana G, Black MJ, Bertram JF. 99 - Development of the Kidney: Morphology and Mechanisms. In: Polin RA, Abman SH, Rowitch DH, Benitz WE, Fox WW, Herausgeber. Fetal and Neonatal Physiology (Fifth Edition) [Internet]. Elsevier; 2017 [zitiert 8. Februar 2025]. S. 953-964.e4. Verfügbar unter: https://www.sciencedirect.com/science/article/pii/B9780323352147000998

10. Eid S, Iwanaga J, Loukas M, Oskouian RJ, Tubbs RS. Pelvic Kidney: A Review of the Literature. Cureus. 10(6):e2775.

11. Gulas E, Wysiadecki G, Cecot T, Majos A, Stefańczyk L, Topol M, u. a. Accessory (multiple) renal arteries – Differences in frequency according to population, visualizing techniques and stage of morphological development. Vascular. 1. Oktober 2016;24(5):531–7.

12. Eldefrawy A, Arianayagam M, Kanagarajah P, Acosta K, Manoharan M. Anomalies of the inferior vena cava and renal veins and implications for renal surgery. Cent Eur J Urol. 2011;64(1):4–8.

13. Pozniak MA, Balison DJ, F T Lee J, Tambeaux RH, Uehling DT, Moon TD. CT angiography of potential renal transplant donors. RadioGraphics [Internet]. 1. Mai 1998 [zitiert 26. Februar 2025]; Verfügbar unter: https://pubs.rsna.org/doi/10.1148/radiographics.18.3.9599383

14. Kumaresan M, Saikarthik J, Sangeetha A, Saraswathi I, Senthil Kumar K, Roselin P. Peri-hilar branching pattern and variations of the renal artery among Indian kidney donors using pre-operative computed tomography angiography: an anatomical study and review. Folia Morphol. 13. Oktober 2021;

15. Negromonte GRP, Bandeira RN, Franca HA. Standardization of the nomenclature of anatomical variants of the renal arteries – a conciliatory proposal.

16. Satyapal KS, Haffejee AA, Singh B, Ramsaroop L, Robbs JV, Kalideen JM. Additional renal arteries: incidence and morphometry. Surg Radiol Anat SRA. 2001;23(1):33–8.

17. Abuelnor M. A Systematic Review of the Prevalence of Anatomical Variations of the Renal Artery. Prensa Médica Argent. 6. Juni 2020;106:1–6.

18. Cases C, García-Zoghby L, Manzorro P, Valderrama-Canales FJ, Muñoz M, Vidal M, u. a. Anatomical variations of the renal arteries: Cadaveric and radiologic study, review of the literature, and proposal of a new classification of clinical interest. Ann Anat - Anat Anz. 1. Mai 2017;211:61–8.

19. Merklin RJ, Michels NA. The variant renal and suprarenal blood supply with data on the inferior phrenic, ureteral and gonadal arteries: a statistical analysis based on 185 dissections and review of the literature. J Int Coll Surg. Januar 1958;29(1 Pt 1):41–76.

20. Budhiraja V, Rastogi R, Anjankar V, Babu CSR, Goel P. Supernumerary Renal Arteries and Their Embryological and Clinical Correlation: A Cadaveric Study from North India. ISRN Anat. 20. Februar 2013;2013:405712.

21. Aremu A, Igbokwe M, Olatise O, Lawal A, Maduadi K. Anatomical variations of the renal artery: a computerized tomographic angiogram study in living kidney donors at a Nigerian Kidney Transplant Center. Afr Health Sci. September 2021;21(3):1155–62.

22. Türkvatan A, Özdemir M, Cumhur T, Ölçer T. Multidetector CT angiography of renal vasculature: normal anatomy and variants. Eur Radiol. Januar 2009;19(1):236–44.

23. Jarral SA, Fatima T, Mirza TM, Farooq U. Prevalence of Anatomical Variant Renal arterial diameter, Early Prehilar Branching and Multiplicity on Contrast Enhanced Computed Tomography Scans. Ann King Edw Med Univ. 29. Juni 2024;30(2):163–70.

24. Zhu J, Zhang L, Yang Z, Zhou H, Tang G. Classification of the renal vein variations: a study with multidetector computed tomography. Surg Radiol Anat. 1. August 2015;37(6):667–75.

25. Karaman B, Koplay M, Özturk E, Basekim CC, Ogul H, Mutlu H, u. a. Retroaortic Left Renal Vein: Multidetector Computed Tomography Angiography Findings and Its Clinical Importance. Acta Radiol. 1. Januar 2007;48(3):355–60.

26. Aljabri B, MacDonald PS, Satin R, Stein LS, Obrand DI, Steinmetz OK. Incidence of Major Venous and Renal Anomalies Relevant to Aortoiliac Surgery as Demonstrated by Computed Tomography. Ann Vasc Surg. 1. November 2001;15(6):615–8.

27. Helical CT evaluation of potential kidney donors: findings in 154 subjects. [Internet]. [zitiert 9. März 2025]. Verfügbar unter: https://www.ajronline.org/doi/epdf/10.2214/ajr.169.5.9353451

28. Chai JW, Lee W, Yin YH, Jae HJ, Chung JW, Kim HH, u. a. CT Angiography for Living Kidney Donors: Accuracy, Cause of Misinterpretation and Prevalence of Variation. Korean J Radiol. 1. August 2008;9(4):333–9.

29. Kok NFM, Dols LFC, Hunink MGM, Alwayn IPJ, Tran KTC, Weimar W, u. a. Complex Vascular Anatomy in Live Kidney Donation: Imaging and Consequences for Clinical Outcome. Transplantation. 27. Juni 2008;85(12):1760.

30. Rubin GD, Alfrey EJ, Dake MD, Semba CP, Sommer FG, Kuo PC, u. a. Assessment of living renal donors with spiral CT. Radiology. Mai 1995;195(2):457–62.

31. Valenzuela Fuenzalida JJ, Vera-Tapia K, Urzúa-Márquez C, Yáñez-Castillo J, Trujillo-Riveros M, Koscina Z, u. a. Anatomical Variants of the Renal Veins and Their Relationship with Morphofunctional Alterations of the Kidney: A Systematic Review and Meta-Analysis of Prevalence. J Clin Med. Januar 2024;13(13):3689.

32. Wondmagegn H, Gebremickael A, George M, Fikadu T, Zewdie TH, Ayele T, u. a. Does a Renal Vascular Variation in the Renal Allograft Determine the Outcome of Renal Transplantation? Experience from the National Kidney Transplantation Center, Ethiopia. Clin Audit. Februar 2022;Volume 14:9–17.

33. McEvoy JW, McCarthy CP, Bruno RM, Brouwers S, Canavan MD, Ceconi C, u. a. 2024 ESC Guidelines for the management of elevated blood pressure and hypertension: Developed by the task force on the management of elevated blood pressure and hypertension of the European Society of Cardiology (ESC) and endorsed by the European Society of Endocrinology (ESE) and the European Stroke Organisation (ESO). Eur Heart J. 7. Oktober 2024;45(38):3912–4018.

34. Song WH, Baik J, Choi EK, Lee HY, Kim HH, Park SM, u. a. Quantitative analysis of renal arterial variations affecting the eligibility of catheter-based renal denervation using multi-detector computed tomography angiography. Sci Rep. 12. November 2020;10(1):19720.

35. Kasprzycki K, Petkow-Dimitrow P, Krawczyk-Ożóg A, Bartuś S, Rajtar-Salwa R. Anatomic Variations of Renal Arteries as an Important Factor in the Effectiveness of Renal Denervation in Resistant Hypertension. J Cardiovasc Dev Dis. 29. August 2023;10(9):371.

36. Kumar N, Dilkash MNA, Rani C. Anatomical Study of Variations in The Renal Vasculature: A Review. Azerbaijan Pharm Pharmacother J. 22. Dezember 2024;23:240–8.

37. Alsharari R, Shantsila E, Lip GYH, Shantsila A. Revisiting the diagnosis of ‘resistant hypertension’: what should we do nowadays’. J Hum Hypertens. April 2022;36(4):337–40.

38. Gulleroglu K, Gulleroglu B, Baskin E. Nutcracker syndrome. World J Nephrol. 6. November 2014;3(4):277–81.

39. Jiang Y, Gan Z, Wang Q, Chen Y, Jiang Y. Bibliometric and visual analysis of research on nutcracker syndrome from 1974 to 2021: A systematic review. Medicine (Baltimore). 5. August 2022;101(31):e29939.

40. Cuéllar i Calàbria H, Quiroga Gómez S, Sebastià Cerqueda C, Boyé de la Presa R, Miranda A, Àlvarez-Castells A. Nutcracker or left renal vein compression phenomenon: multidetector computed tomography findings and clinical significance. Eur Radiol. 1. August 2005;15(8):1745–51.

41. Davran R, Helvaci MR, Davarci M. Left renal atrophy. Int J Clin Exp Med. 2014;7(6):1603–6.

42. Cumming RE, Schroeder CF. Renal Atrophy. J Urol. 1937;37(4):407–36.

43. Shindo S, Bernstein J, Arant BS. Evolution of renal segmental atrophy (Ask-Upmark kidney) in children with vesicoureteric reflux: Radiographic and morphologic studies. J Pediatr. 1983;102(6):847–54.

44. Xiangrui Y, Xiong W, Xi W, Yuanbing J, Shenqiang Q, Yu G. Clinical Assessment of Risk Factors for Renal Atrophy after Percutaneous Nephrolithotomy. Med Sci Monit. 2020;26:1–6.

45. Caroli A, Remuzzi A, Lerman LO. Basic principles and new advances in kidney imaging. Kidney Int. 2021;100(5):1001–11.

46. Sohail MA, Sedor J, Kirksey L, Blaha SC, Hofmann H. Unilateral atrophic kidney in a 45-year-old woman. Cleve Clin J Med. 2022;89(8):465–71.

47. Marboeuf P, Delsart P, Hurt C, Villers A, Hossein-Foucher C, Beregi JP, u. a. Conduite à tenir devant une atrophie rénale chez le patient hypertendu : l’expérience lilloise. Presse Médicale. April 2010;39(4):e67–76.

48. Tonelli M, Wiebe N, Knoll G, Bello A, Browne S, Jadhav D, u. a. Systematic review: Kidney transplantation compared with dialysis in clinically relevant outcomes. Am J Transplant. 2011;11(10):2093–109.

49. Bachul PJ, Osuch C, Chang E sle, Bętkowska-Prokop A, Pasternak A, Szura M, u. a. Crossing Anatomic Barriers—Transplantation of a Kidney with 5 Arteries, Duplication of the Pyelocalyceal System, and Double Ureter. Cell Transplant. Oktober 2017;26(10):1669–72.

50. Kamali K, Abbasi MA, Ani A, Zargar MA, Shahrokh H. Renal Transplantation in Allografts with Multiple Versus Single Renal Arteries. Saudi J Kidney Dis Transplant. April 2012;23(2):246.

51. Jelin A. Renal agenesis. Am J Obstet Gynecol. 1. November 2021;225(5):B28–30.

52. More MS, Togale MD, Bhimalli S, Dixit D, Desai SP. A study of congenital anomalies of human adult cadaveric kidneys. Int Med J. 2015;2(6).

53. Kang WY, Sung DJ, Park BJ, Kim MJ, Han NY, Cho SB, u. a. Perihilar branching patterns of renal artery and extrarenal length of arterial branches and tumour-feeding arteries on multidetector CT angiography. Br J Radiol. März 2013;86(1023):20120387.

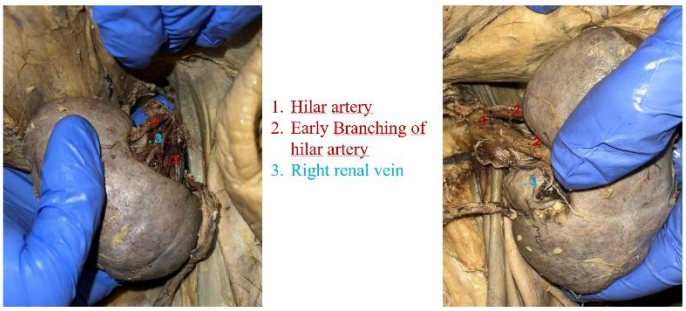
54. Satyapal KS. Classification of the drainage patterns of the renal veins. J Anat. April 1995;186(Pt 2):329–33.

55. García-Barrios A, Cisneros-Gimeno AI, Celma-Pitarch A, Whyte-Orozco J. Anatomical study about the variations in renal vasculature. Folia Morphol. 2024;83(2):348–53.

56. Vilhova I, Kryvko YY, Maciejewski R. The radioanatomical research of plural renal arteries. Folia Morphol. 2001;60(4).

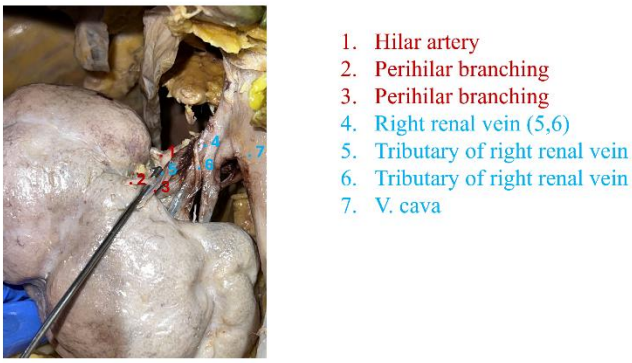
12 Annexes

Annex 1 Images of Renal Vasculature dissection

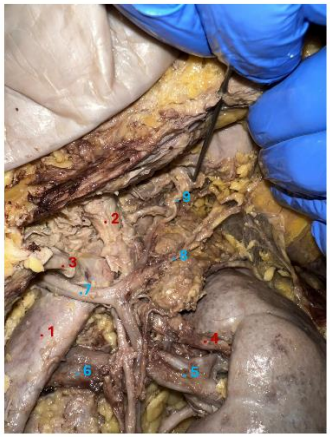


Annex 1, Figure 1A Case 1 – Right renal vasculature (anterior and posterior view) with early branching.

Annex 1, Figure 1B Case 1 – Left renal vasculature without variations.



Annex 1, Figure 2A Case 2 – Right renal vasculature with Perihilar branching and venous tributaries.



1. Aorta
2. Celiac trunk
3. Superior mesenteric artery
4. Hilar artery

Circumaortic renal vein:

5. Common trunk of left renal vein
6. Left renal vein (posterior to Aorta abdominalis)
7. Left renal vein (anterior to Aorta abdominalis)
8. Left adrenal vein
9. Left gastric vein

Annex 1, Figure 2B Case 2 – Left renal vasculature with circumaortic left renal vein

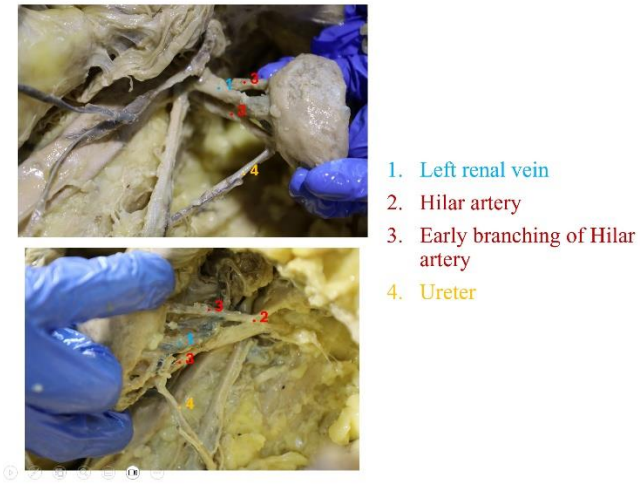
1. Hilar artery
2. Perihilar branching superior artery
3. Perihilar branching inferior artery
4. Perihilar superior polar artery
5. Right renal vein
6. V. cava

Annex 1, Figure 3A Case 3 – Right renal vasculature with perihilar branching.

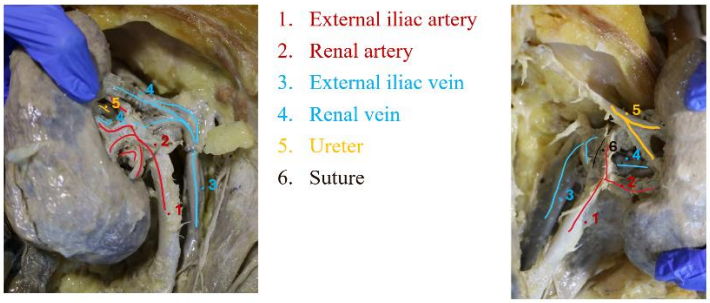
1. Hilar artery
2. Aortic superior polar artery
3. Aorta abdominalis
4. Left renal vein
5. Abnormal reflux Type B (Vena hemiazygos drainage)

Annex 1, Figure 3B Case 3 – Left renal vasculature with aortic superior polar artery and abnormal reflux into vena hemiazygos.

Annex 1, Figure 4A Case 4 – Right renal vasculature with early branching and aortic superior polar artery, Kidney atrophied.



Annex 1, Figure 4B Case 4 – Left renal vasculature with early branching, Kidney atrophied.

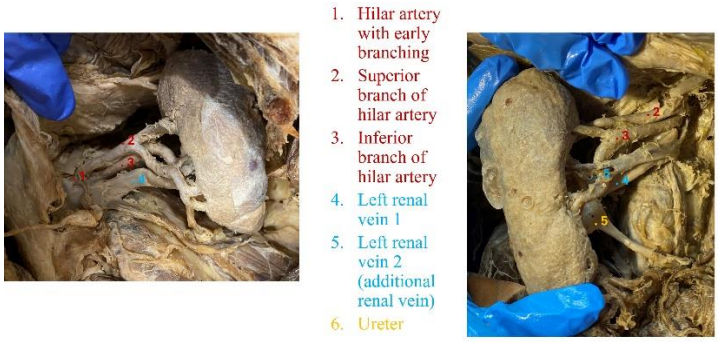


Annex 1, Figure 4C Case 4 – Kidney transplant in right iliac fossa.

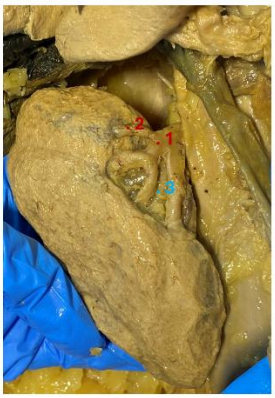
Annex 1, Figure 5A Case 5 – Right kidney vasculature with aortic superior polar artery.

Annex 1, Figure 5B Case 5 – No kidney and no renal vasculature visible.

Annex 1, Figure 6A Case 6 – Right kidney vasculature with aortic superior polar artery and additional renal vein.

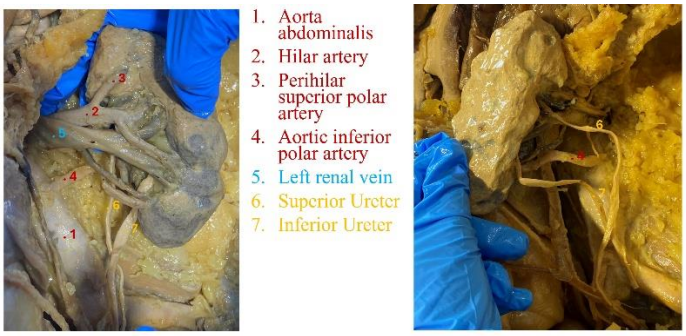


Annex 1, Figure 6B Case 6 – Left kidney vasculature with early branching and additional renal vein.



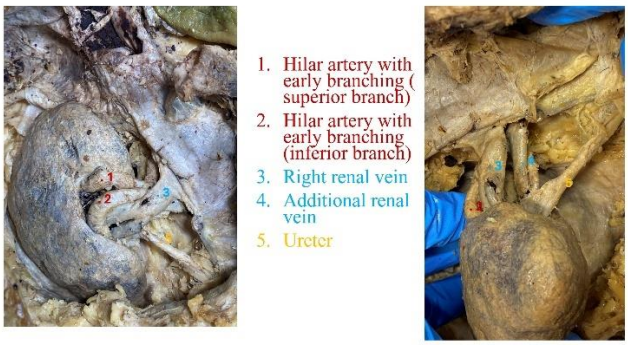
1. Hilar artery with perihilar branching
2. Perihilar superior polar artery
3. Right renal vein

Annex 1, Figure 7A Case 7 – Right kidney vasculature with perihilar branching and perihilar superior polar artery.



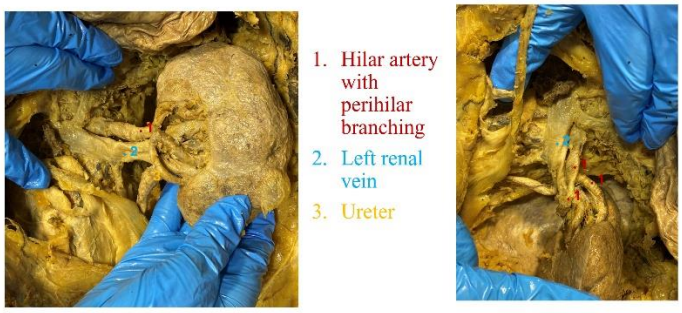
1. Aorta abdominalis
2. Hilar artery
3. Perihilar superior polar artery
4. Aortic inferior polar artery
5. Left renal vein
6. Superior Ureter
7. Inferior Ureter

Annex 1, Figure 7B Case 7 – Left kidney vasculature with aortic inferior polar and perihilar superior polar artery.

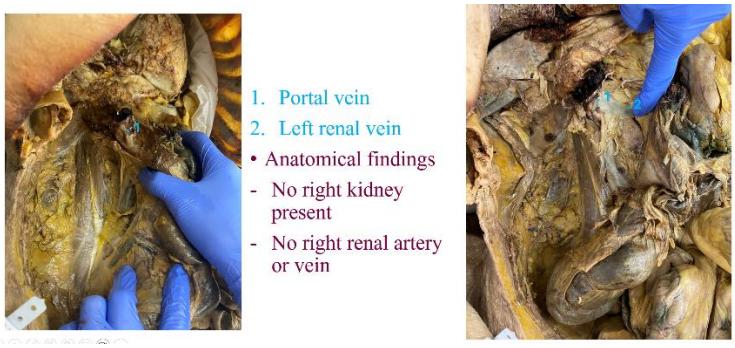


1. Hilar artery with early branching (superior branch)
2. Hilar artery with early branching (inferior branch)
3. Right renal vein
4. Additional renal vein
5. Ureter

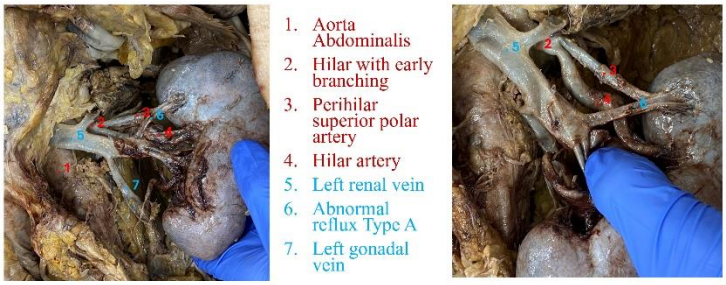
Annex 1, Figure 8A Case 8 – Right kidney vasculature with early branching and an additional renal vein.



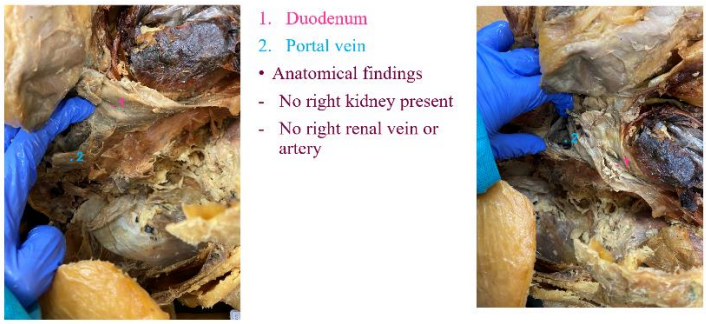
Annex 1, Figure 8B Case 8 – Left kidney vasculature with perihilar branching.



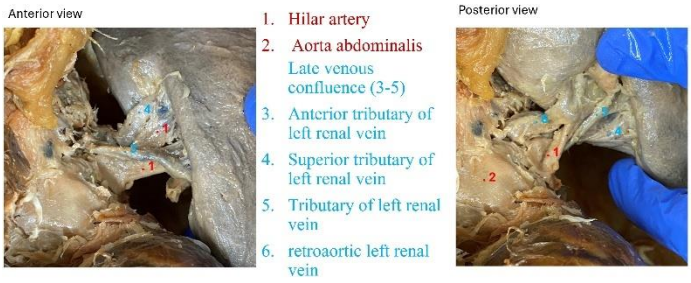
Annex 1, Figure 9A Case 9 – No kidney and no renal vasculature.



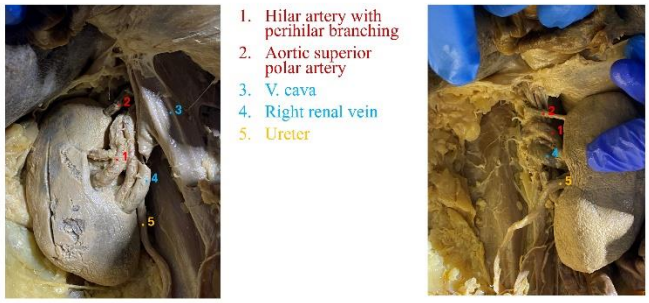
Annex 1, Figure 9B Case 9 – Left kidney vasculature with abnormal reflux type A.



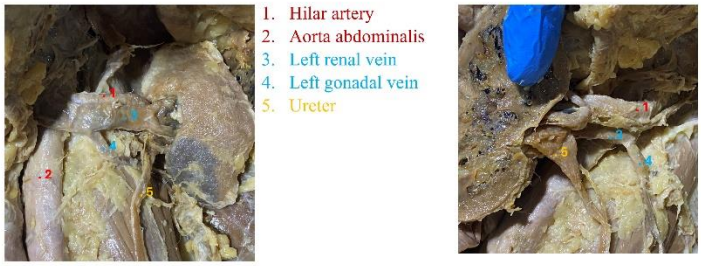
Annex 1, Figure 10A Case 10 – No kidney and no renal vasculature.



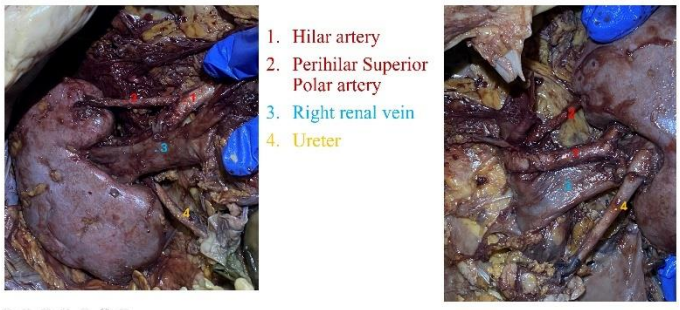
Annex 1, Figure 10B Case 10 – Left kidney vasculature with late venous confluence and retroaortic left renal vein.



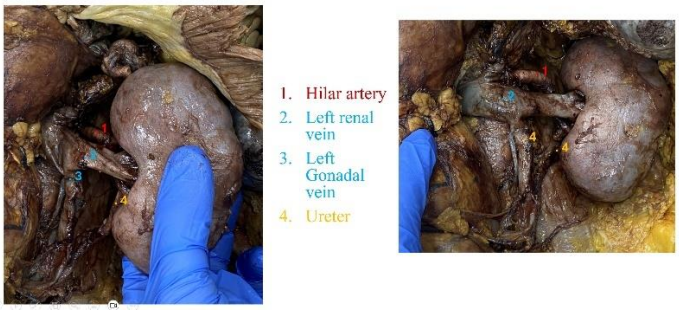
Annex 1, Figure 11A Case 11 – Right kidney vasculature with perihilar branching and aortic superior polar artery.



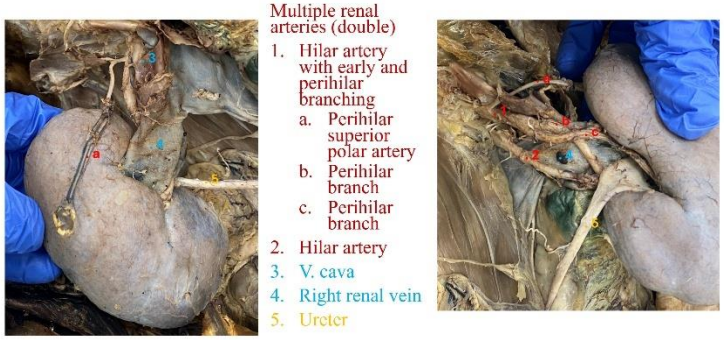
Annex 1, Figure 11B Case 11 – Left kidney vasculature without variations.



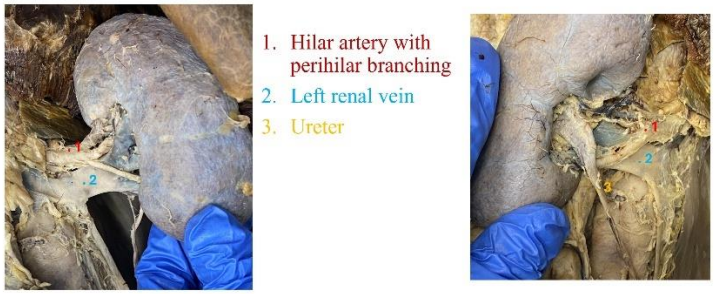
Annex 1, Figure 12A Case 12 – Right kidney vasculature with perihilar superior polar artery.



Annex 1, Figure 12B Case 12 – Left kidney vasculature without variations.



Annex 1, Figure 13A Case 13 – Right kidney vasculature with double renal arteries, perihilar and early branching.



Annex 1, Figure 13B Case 13 – Left kidney vasculature with perihilar branching.