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Three-Dimensional Anatomical Analysis of the Vascular System of the Human Kidney

Abuselim Zagidovich Vezirkhanov*, Petr Alexandrovich Sysoev, Edgar Sabirovich Kafarov

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Abstract

The study aimed to review the variants of renal artery division and the formation of renal veins in the renal hilum according to the data of corrosive preparations. The authors studied 124 polychrome corrosive renal vessel preparations. The preparations were subjected to three-dimensional scanning. The three-dimensional projection and topographic and anatomical features of the structure of the arterial and venous renal vessels were determined. As a result, the authors determined the di- and trichotomous variants of the division of the renal artery, A. renalis, into the branches of the 2nd order, that is, zonal arteries, a. zonal, (II). It was revealed that in 70.9% of cases the renal artery in the renal hilum was dichotomously divided into zonal arteries, (a. zonal) (II), wherein 59.6% of cases, the authors observed division of the renal artery into ventral and dorsal branches, further dividing into the ventral and dorsal parts of the renal parenchyma. In the venous system of the kidney, it was found that in 58.8% of cases, the renal vein, V. renalis (I), was formed from two venous vessels in the renal hilum, wherein 36.4% of cases, the renal vein was formed from the superior and inferior polar veins relative to the horizontal plane, and in 22.4% of cases, it was formed from the ventral and dorsal veins. It was revealed that in 36.1% of cases, the main renal vein, V. renalis (I), in the renal hilum was formed from three venous vessels, where several variants were found.

Keywords: Kidney, Renal veins, Renal artery, 3D-Modeling

Introduction

In urological practice, when performing organ-preserving operations or segmental resections on the kidneys, it is necessary to have accurate information about the topographic features of the structure of the renal arterial and venous vessels, about possible anomalies of the discharge of these blood vessels or their variant anatomy to avoid the occurrence of life-threatening bleeding (Melman *et al.*, 2016; Kushlinskii *et al.*, 2018; Denizet *et al.*, 2019; Fonseka, 2021). Thus, in urology and vascular surgery, clinicians are interested in clarifying not only the structure but also the position of the renal vessels in the hilum (Tabucanon & Tang, 2020; Fonseka, 2021). Knowledge of the options for the topography of tubular structures at the hilum is important, both when choosing operative access to the pelvis or vessels of the kidneys, and makes it possible to determine the degree of renal venous hypertension in pathological conditions or compression at the hilum (Klatte *et al.*, 2015; Vagabov *et al.*, 2015; Gupta *et al.*, 2016; Melman *et al.*, 2016; Ivandaev *et al.*, 2018; Kafarov *et al.*, 2019; Majos *et al.*, 2019; Has & Sarac Sivrikoz, 2020).

The widespread use of radiological research methods in clinical practice also required clarification of many issues related to the anatomy of the Renal Veins (RVs) and Renal Arteries (RAs), and especially their location and intra-organ topography (Teplov *et al.*, 2016; Steenman & Lande, 2017; Kushlinskii *et al.*, 2018; Askerova *et al.*, 2019; Denizet *et al.*, 2019; Kafarov *et al.*, 2019; Kolsanov *et al.*, 2019; Song *et al.*, 2019). Thus, with the advent of powerful diagnostic equipment, it became possible to identify all kinds of anomalies of the renal arterial and venous vessels and see potential defects or assess their hemodynamic characteristics. Computed Tomography (CT) has allowed clinicians to obtain information about the major renal vessels (Kushlinskii *et al.*, 2018; Majos *et al.*, 2018; Song *et al.*, 2019; Fonseka, 2021). However, from the literature, we learned that the disadvantage of CT of these vessels was that the radiation diagnostician received disconnected information about the arterial and venous bed of the human kidney, that is, there was no simultaneous visualization of both arterial and venous vessels of the human kidney (Denizet *et al.*, 2019; Shormanov & Los, 2019). According to the authors, CT of the renal vessels with subsequent 3D modeling reveals mainly the arterial system of the human kidney with partial visualization of the renal venous system, where the main RVs and the vessels that form them are revealed, which is insufficient for performing any surgical interventions on the kidney (Denizet *et al.*, 2019; Shormanov & Los, 2019). In this regard, in urological and oncological practice, due to the lack of the possibility of simultaneous visualization of both arterial and venous vessels of the kidney, it is not possible to obtain true information about the topographic features of the structure of the arterial and venous bed of the kidney.

However, even though today more and more attention is paid to the renal arterial and venous bed, there is no common point of view on

Abuselim Zagidovich Vezirkhanov*, Edgar Sabirovich Kafarov
Department of Normal and Topographic Anatomy with Operative Surgery, Chechen State University, Grozny, Chechen Republic, Russia.

Petr Alexandrovich Sysoev
Department of Urology, Faculty of Advanced Training for Doctors, Institute of Moscow Regional Research Clinical, Moscow, Russia.

***E-mail:** vezirkhanov.a.z@bk.ru

the frequency of variants of the extra- and intrarenal division of the RAs and the formation of RVs, their number, or the variants of location in the renal hilum (Zotikov *et al.*, 2016; Geraci *et al.*, 2017; Majos *et al.*, 2019; Dumas *et al.*, 2021). Variants of the division of the RAs and the formation of RVs in the works by different authors have quite noticeable differences in percentage (Kafarov *et al.*, 2015; 2019b; 2019c). There is almost no detailed information about the sources and variants of the formation of RVs in the renal hilum (Melman *et al.*, 2016; Steenman & Lande, 2017; Denizet *et al.*, 2019; Kolsanov *et al.*, 2019; Has & Sarac Sivrikoz, 2020).

Based on the literature data, it can be seen that the arterial and venous systems of the human kidney, both intra- and extra-organ parts of it, are distinguished by pronounced individual variability, which requires their analysis and systematization.

Scope of the Study

The study aims to review the variants of the RA division and the RV formation in the renal hilum according to the data of polychrome corrosive preparations of the arterial and venous vessels of the human kidney.

Materials and Methods

The material for the study was 124 polychrome corrosive preparations of arterial and venous vessels of the kidneys, made from the corpse kidneys of people of both genders, aged 22 to 75 years, who had died from diseases not related to kidney pathology. The preparations were acquired through grant No. 20-315-90008 from the Russian Foundation for Basic Research (RFBR). Since we studied the variants of division and types of branching of the renal arterial and venous bed, which do not change during ontogenesis and are genetically determined, we did not study those vessels from the age aspect, which is consistent with the data of F.R. Asfandiyarov (Steenman & Lande, 2017).

The polychrome corrosive preparations of the renal vessels that we had acquired had X-ray-positive properties since they had been injected with Protacryl (on request) mixed with a radiopaque substance, Barium Sulfate. A patent application was filed for Polymer X-ray contrast composition for the manufacture of corrosive anatomical preparations (Patent No. 145561 dated December 28, 2020, O. K. Zenin, E. S. Kafarov, A. Z. Vezirkhanov, I. U. Vagabov). The study of the material was carried out in a comprehensive manner using several consistently conducted techniques.

Study Algorithm

1. Polychrome corrosive preparations of arterial and venous vessels of the kidney were photographed using a Sony Cybershot DSC-RX10M4 Black digital camera. All polychrome corrosive preparations of arterial and venous vessels of the kidney for digitization were subjected to 3D scanning using a 3D microcomputer tomographic system RayScan 130 (Germany), with a current strength of 132 mAs, a voltage of 140 kV, a helix pitch of 1.0 mm and subsequent 3D modeling (Agreement No. 5 dated July 18, 2020).
2. Extraorgan branches of the RA and RV were observed on polychrome corrosive preparations of arterial and venous vessels of the kidney, and the following data were documented: a) the number of RAs and RVs in the renal hilum; b) the topography of the RAs and RVs at the renal hilum. Subsequently, polychromatic corrosive preparations of arterial and venous vessels of the kidney underwent partial defragmentation and disposal of peripheral vessels up to the exposure of the main large arterial and venous trunks.
3. In the Mimics-8.1 and 3D-max software, after 3D-scanning of polychromatic corrosion preparations of arterial and venous vessels of the kidney, we made a 3D projection of arterial and venous vessels of the kidneys relative to the frontal, horizontal, and sagittal planes. We studied a 3D projection and topographic and anatomical features of the arterial vessels of the kidneys relative to the venous vessels and the pelvis.
4. In a 3D modeling software, we studied the following features of the extra-organ branches of the RA and RV in 3D projection: a) the number of RAs and RVs in the renal hilum, the topography of the RAs and RVs in the hilum of the kidney; b) the variants of the division of the RA and formation of RVs at the renal hilum in 3D projection, the extra-organ division of the main RA and formation of the main RV, the intra-organ division of the RA and formation of the RV; c) the division types of the RA and fusion types of the RV inside the kidney, depending on the variants of division and fusion at the hilum of each of its branches and sub-branches in a 3D projection (the magistral type of artery branching and vein fusion or the loose type of artery branching and vein fusion).
5. In the *Mimics-8.1* and *3D-max* software after 3D-scanning of polychromatic corrosion preparations of arterial and venous vessels of the kidney, we made a 3D projection of arterial and venous vessels of the kidneys relative to the frontal, horizontal, and sagittal planes. We determined a 3D projection and topographic anatomical features of the arterial and venous vessels of the human kidneys.
6. All the obtained digital material and the data of instrumental research methods were processed by the methods of variation statistics using a workstation with an *Intel Core2Duo T5250 1.5 GHz processor, RAM* up to *2 GB* on the *Windows 7* platform. In the course of the work, we used the Excel application package from *Microsoft Office 2007*.

Results and Discussion

We performed a 3D anatomical analysis of the arterial and venous vessels of the kidney using polychromatic corrosion preparations, which revealed variants of the division of the right and left main RAs and variants of the formation of the right and left RVs in the renal hilum relative to the sagittal plane, tangent to the medial the edges of the kidneys in both genders **(Table 1)**.

Table 1. Extra- and Intrarenal Variants of RA Division

Men			
Intrarenal division variant		Extrarenal division variant	
Right RA	Left RA	Right RA	Left RA
34.4%	38.4%	65.6%	61.8%
Women			
Intrarenal division variant		Extrarenal division variant	
Right RA	Left RA	Right RA	Left RA
35.3%	36.4%	64.7%	63.6%

As a result of the studies, it was found that in men in 34.4% of cases, division of the main right RA occurred at the renal hilum, that is, lateral to the sagittal plane, tangent to the medial border of the kidney (the intrarenal variant of RA division), and in 65.6% cases, we found the variant of the main RA division medial to the sagittal plane, tangent to the medial border of the kidneys, that is, at a distance from the renal hilum, closer to the abdominal aorta (the extrarenal variant of the RA division). Further, it was found that on the left, the division of the main RA in 38.2% of cases occurred at the renal hilum, that is, laterally from the sagittal plane, tangent to the medial border of the kidneys (an intrarenal variant of main RA division), and in 61.8% of cases, we observed the extrarenal variant of RA division, that is, medial to the sagittal plane, tangent to the medial border of the kidneys **(Table 1)**.

In women, it was found that in 35.3% of cases, the division of the right main RA occurred at the renal hilum, that is, lateral to the sagittal plane tangential to the medial border of the kidney (the intrarenal variant of the RA division), and in 64.7% of cases, its division occurred medially from the sagittal plane of the tangent to the medial border of the kidney, that is, closer to the abdominal part of the aorta, (the extrarenal variant of the main RA division).

On the left side, the division of the main RA in 36.4% of cases occurred in the renal hilum, that is, lateral to the sagittal plane of the tangent to the medial border of the kidney (the intrarenal variant of the main RA division), and in 63.6% of cases, the extrarenal variant of RA division was revealed, that is, medial to the sagittal plane, tangent to the medial border of the kidney.

Further, we identified the following variants of the RV formation in the renal hilum relative to the sagittal plane tangential to the medial border of the kidney: It was found that in men in 32.6% of cases, the right RV was formed at the renal hilum, that is, lateral to the sagittal plane, tangent to the medial border of the kidney (the intrarenal variant of the RV formation), in 67.4% of cases, the formation of the RV occurred medially from the sagittal plane, tangent to the medial border of the kidneys, that is, at a distance from the renal hilum, closer to the abdominal aorta (the extrarenal variant of the RV formation).

Further, it was found that on the left side, the formation of the main RV in 36.3% of cases occurred at the renal hilum, that is, lateral from the sagittal plane, tangent to the medial border of the kidneys (the intrarenal variant of the RV formation), and in 63.7% of cases we observed the extrarenal variant of the RV formation, that is, medial to the sagittal plane, tangent to the medial border of the kidneys **(Table 2)**.

Table 2. Extra- and Intrarenal Variants of the RV formation

Men			
Intrarenal formation variant		Extrarenal formation variant	
Right RV	Left RV	Right RV	Left RV
32.6%	36.3%	67.4%	63.7%
Women			
Intrarenal formation variant		Extrarenal formation variant	
Right RV	Left RV	Right RV	Left RV
34.6%	31.4%	65.4%	68.6%

In women, it was found that in 34.6% of cases the main RV was formed at the renal hilum, that is, lateral to the sagittal plane tangent to the medial border of the kidney (the intrarenal variant of the RV formation), and in 65.4% of cases, we observed a more medial variant of its formation from the sagittal plane of the tangent to the medial border of the kidney, that is, closer to the abdominal aorta, (the extrarenal variant of the main RV formation). On the left side, the formation of the main RV in 31.4% of cases occurred in the renal hilum, that is, lateral from the sagittal plane of the tangent to the medial border of the kidney (the intrarenal variant of the main RV formation), and in 68.6% of cases, we saw a variant of its formation more medially from the sagittal plane, tangent to the medial border of the kidney (the extrarenal variant of the main RV formation).

We carried out a 3D anatomical analysis of the variants of the division of the main RAs and variants of the formation of the main RVs in the renal hilum. Thus, it was found that on 88 polychrome corrosive preparations of arterial and venous vessels of human kidneys out of 124 in this group, the main RA divided into two branches, which was found in 70.9% of cases. At the same time, the division of the main RA relative to the frontal plane into the ventral and dorsal branches was revealed in 59.6% of cases (74 out of 88 corrosive preparations). In 11.2% of cases (14 preparations), the main RA, relative to the horizontal plane, was divided into the superior pole and inferior pole branches. Further, we observed some variants where on 36 polychrome corrosive preparations of renal vessels out of 124, the main RA divided into 3 branches, which was found in 29.0% of cases. It was found that out of 36 corrosive preparations of renal vessels in 13.6% of cases (17 preparations), the main RA was divided into ventral, dorsal, and superior pole branches in the renal hilum relative to the frontal and horizontal planes. The ventral and dorsal branches of the main RA were divided into the parenchyma of the anterior and posterior surfaces of the inferior pole of the kidney. The superior pole of the main RA branches into the parenchyma of the ventral and dorsal half of the superior pole of the kidney. In 10.4% of cases (13 preparations), the division of the main RA relative to the frontal and horizontal planes into ventral, dorsal and inferior pole branches was revealed. The ventral branch was positioned in the anterior half of the inferior pole of the kidney, and the dorsal branch was positioned in the same way on the posterior surface of the inferior pole of the kidney. The inferior pole branch of the main

RA was positioned with its branches in the ventral and dorsal half of the inferior pole of the kidney.

Further, the study found that in 3.2% of cases (4 preparations), the main RA was divided relative to the frontal plane into the superior pole, central and inferior pole branches. The branches of the superior pole artery were positioned in the ventral and dorsal parts of the superior pole of the kidney. The central artery was positioned in the central parts of the renal parenchyma from the ventral and dorsal surfaces, and the inferior polar artery was positioned in the ventral and dorsal parts of the inferior pole of the kidney. In 1.6% of cases (2 preparations), variants were identified where the RA looked like a single arterial trunk.

The results of the topographic and anatomical analysis of arterial and venous vessels of the kidneys revealed a variety of forms of division of the main RA and fusion of venous vessels that formed the main RV in the area of the renal hilum.

The study of the variants of the formation of the main RV at the renal hilum established that on 73 polychromic corrosion preparations of arterial and venous vessels of the human kidneys out of 124 in this group, the main RV was formed from two venous vessels, which was revealed in 58.8% of cases. It was found that in 36.4% of cases, the main RV relative to the horizontal plane was formed from the superior and inferior polar veins, and in 22.4% of cases from the ventral and dorsal veins, at $p \leq 0.05$.

Further, variants were identified, where on 45 polychromatic corrosive preparations out of 124, the main RV was formed from three venous vessels, which amounted to 36.1% of cases, at $p \leq 0.05$. At the same time, in 18.4% of cases, the RV was formed from the superior polar, central, and inferior polar veins located in the same projection. It was revealed that the superior pole vein was involved in the drainage of the ventral and dorsal half of the superior pole of the kidney. The central one was involved in venous drainage of the central part of the renal parenchyma, and the inferior polar vein drained the ventral and dorsal parts of the inferior pole of the kidney.

Later, in the study of corrosive preparations, we observed a variant of the formation of the main RV relative to the frontal and horizontal planes from the ventral, dorsal, and superior polar veins, which was found in 11.2% of cases. The ventral and dorsal veins were involved in the drainage of the anterior and posterior parts of the inferior pole of the kidney, and the branches of the superior pole vein drained the parenchyma of the superior pole of the kidney from both the ventral and dorsal sides. Finally, in 6.5% of cases, it was found that the formation of the main RV occurred from the ventral, dorsal, and inferior polar veins relative to the frontal and horizontal planes. At the same time, the ventral and dorsal veins drained the parenchyma of the inferior pole of the kidney on both sides, and the superior pole vein drained the parenchyma of that pole.

We would like to note that the remaining variants of the formation of the RV accounted for less than 5.0% of cases, with $p \leq 0.05$.

Thus, summarizing all of the above, it should be noted that in the study of polychrome corrosion preparations of the extra-organ section of the renal vessels, we have established extra- and intrarenal variants of the division of the main RA, A. renalis, in men and women in the renal hilum on the branches of the second order, (a. zonal) (II). It was revealed that, regardless of gender characteristics and the side of the body, the extrarenal variant of the division of the main RA, A. renalis, most often prevailed. On average, it amounted to $(X \pm m)$ 65.1 ± 3% and exceeded the intrarenal variant, where the average value was $(X \pm m)$ 34.9 ± 3%.

In the study of polychromic corrosion preparations of the intra-organ part of the arterial vessels of the kidneys, di - and trichotomous variants of the division of the main trunk of the RA, A. renalis, into the branches of the second order, that is, zonal arteries, a. zonal, (II) it was revealed that in 70.9% of cases, the main RA in the renal hilum was dichotomously divided into zonal arteries, (a. zonal) (II), wherein 59.6% of cases, the main RA was divided into ventral and dorsal branches, separating in the ventral and dorsal parts of the renal parenchyma, and in 11.2% of cases, it was divided in the renal hilum into the superior and inferior polar arteries. In 29.0% of cases, trichotomous variants of RA division were observed.

In parallel with the arterial system of the kidney, a 3D anatomical analysis of the venous system of the human kidney was carried out, where it was found that in 58.8% of cases, the main RV, V. renalis (I), in the renal hilum was formed from two venous vessels, wherein 36.4% of cases, the main RV relative to the horizontal plane was formed from the superior and inferior polar veins, and in 22.4% of cases, it was formed relative to the frontal plane from the ventral and dorsal veins. It was revealed that in 36.1% of cases, the main RV, V. renalis (I), in the renal hilum was formed from three venous vessels, where several variants had been found.

Conclusion

1. It was found that in men in 34.4% of cases, the right RA was divided intrarenally, and in 65.6% of cases, extrarenally. The left VA was divided intrarenally in 38.2% of cases, and extrarenally in 61.8% of cases. In women, in 35.3% of cases, the right RA was divided intrarenally, and in 64.7% of cases, extrarenally. It was revealed that the left RA in 36.4% of cases was divided intrarenally, and in 63.6% of cases extrarenally. In men, in 32.6% of cases, the right RV was formed intrarenally, and in 67.4% of cases, extrarenally. The left RV was formed intrarenally in 36.3% of cases, and extrarenally in 63.7% of cases. In women, the right RV was formed intrarenally in 34.6% of cases, and extrarenally in 65.4% of cases. The left RV was formed intrarenally in 31.4% of cases, and an extrarenal variant of its formation was observed in 68.6% of cases.
2. In 70.9% of cases, the RA was dichotomously divided into zonal arteries, where in 59.6% of cases, the RA was divided into ventral and dorsal branches, and in 11.2% of cases, into superior and inferior pole branches. In 29.0% of cases, trichotomous variants of RA division were observed: in 13.6% of cases, the RA was divided into ventral, dorsal, and

superior pole arteries relative to the frontal and horizontal planes; in 10.4% of cases, the RA was divided into ventral, dorsal, and inferior polar arteries relative to the frontal and horizontal planes; and in 3.2% of cases, the main RA was divided into the superior polar, central, and inferior polar arteries relative to the frontal plane. We did not observe the division of the main RA into a larger number of arteries.

3. It was found that in 58.8% of cases the RV was formed from two venous vessels, wherein 36.4% of cases, the RV was formed from the superior and inferior polar veins relative to the horizontal plane, and in 22.4% of cases, it was formed from the ventral and dorsal veins relative to the frontal plane. It was observed that in 36.1% of cases, the RV was formed in the renal hilum from three veins, where several variants were found: in 18.4% of cases, the RV was formed in the renal hilum from the superior polar, central, and inferior polar veins located in the same projection; in 11.2% of cases, the RV was formed from the ventral, dorsal, and superior polar veins relative to the frontal and horizontal planes; and in 6.5% of cases, the RV was formed from the ventral, dorsal, and inferior polar veins relative to the frontal and horizontal planes.

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Ethics statement: None

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