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Research paper

Variant Anatomy of The Portal Vein According to 3D Modeling Data

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Abstract

The study aimed to evaluate the variant anatomy of the portal vein based on computed tomography. Materials and methods. The material was the results of 224 multispiral computed tomography of abdominal organs from the archive of clinics of Samara State Medical University (Samara, Russia) for 2018-2019. Plug-ins were used in the Luch and Avtoplan programs to mathematically model and create 3D models of the vascular bed. These programs make it possible to obtain 3D models based on multispiral computed tomography data. The portal vein confluence variant and angle parameters formed by the trunk and roots of the portal vein were studied, considering the gender and age of the patients. Results. The study found that type A confluence occurred in 45.5% of cases. Type B confluence was detected in 26.8%. Type C confluence occurred in 16.5%. There were no statistically significant differences in the angles formed by the trunk and roots of the portal vein in patients of different age groups and genders. Portal vein type A division was detected in 71.9% of observations, and portal vein type B division was detected in 20.1%.

Keywords: *Portal Vein; Computed Tomography; Confluence, 3D; Abdominal Organs.*

1. Introduction

The scientific literature lacks information on unified terminology and systematization of portal vein anatomical variants, and there are no unified approaches and principles for studying them in variant anatomy. Thus, as before, there is no unified classification of variants of formation and division of the portal vein [1]. There is no commonality in determining what is considered the root of the portal vein and what is its tributary [2].

The data presented on the morphometric characteristics of the portal vein vary significantly, and the data on its extreme forms and the range of anatomical differences are contradictory. Discussions continue about the boundaries of the norm beyond which pathology begins [3], [4]. Modern definitions describe extreme forms as a deviation from the norm without a clear disruption of the function of the anatomical and physiological system. Still, the very concept of norm is controversial. What is considered normal concerning the structure of the human body is arbitrary, based on the experience of morphological research or agreements between specialists, and can vary significantly [5].

Today, the issue of individualization in determining the norm and its boundaries is increasingly considered in medicine. Still, studies characterizing the range of anatomical differences in the portal vein, defined by gender, age, or constitutional characteristics, are practically non-existent, and the available data often contradict each other [4].

Reliable visualization of the area of interest is important in assessing anatomical variations. When studying the portal vein, researchers traditionally used dissection methods, injection, and corrosion techniques on corpses. These anatomical research methods, which have been used for several centuries, are still relevant today, but they allow one to study variant anatomy only post-mortem. Post-mortem changes and non-compliance with the research methodology can significantly distort the results. The expansion of scientific and technical capabilities of medicine and the emergence of modern diagnostic and imaging tools such as multispiral computed tomography (MSCT), magnetic resonance imaging (MRI), ultrasound scanning, and intravital endoscopy allow studying the structural variants of organs and their systems and establishing the range of variability and expected variants of the organ anatomy in each patient in vivo [6].

The study aimed to evaluate the variant anatomy of the portal vein using computed tomography (CT).

2. Materials and Methods

Two hundred twenty-four patients were subjected to computer simulation of medical images obtained from MSCT. The study's criteria included the subjects' age, which was 20-90 years inclusive; absence of CT signs of pathology of the upper floor of the abdominal cavity; absence of CT signs of portal hypertension and portal vein thrombosis; and high-quality CT images for constructing a 3D vascular model. The 3D reconstruction of the vascular bed was performed using specialized plug-ins in the Luch and Avtoplan medical imaging software. These software platforms have been validated for 3D anatomical reconstruction from medical imaging, with Autoplan demonstrating

capability for precise manual segmentation and virtual morphometry tools in various clinical applications [7]. DICOM files were imported and processed to generate 3D models for analysis. Portal vein confluence types and intrahepatic branching variants were classified based on the 3D reconstructions using the Krumm et al. [8] and Nakamura et al. [9] classifications. Cases not meeting image quality requirements for accurate 3D model construction were excluded from the study. The main advantage of these programs is the ability to perform segmentation and 3D modeling within a unified workflow, supporting clinical planning applications [7]. The primary limitation is dependence on CT image quality, as noted by the requirement to exclude cases with inadequate venous enhancement and continuity.
Subjects that did not meet the specified criteria were excluded from the study.
We used the classification developed by Krumm et al. [8] to determine the type of confluence.
We used the classification developed by Nakamura et al. [9] to describe the variants of portal vein division.
All patients participating in the study underwent CT scanning in the standard abdominal examination position. The examination protocol at the first stage included a preliminary native examination of the abdominal organs to clarify the scanning area and assess the condition of the abdominal cavity and retroperitoneal space. The second stage involved intravenous bolus administration of an iso-osmolar contrast agent (Omnipak-350). The purpose of bolus contrast enhancement is to differentiate the phases of contrast. Arterial, venous, and parenchymal phases are distinguished. On average, the arterial phase, in which arterial filling is visualized, begins 20-30 seconds after the start of contrast administration. After 40-60 seconds, the venous phase begins, during which the contrast of the veins is visualized. The volume of contrast agent administered ranged from 100 to 150 ml, the injection rate was 3-5 ml/s, and the average radiation load was 11.3 mSv. This allowed us to study the anatomical relationships of organs at the slice level with high accuracy and the variant anatomy of the vascular bed and to visualize branches up to 1 mm in diameter.
The result (tomographic images) is a set of 2D transverse images (slices) containing a matrix of intensity values in a black-and-white image. Tomographic images are saved as a DICOM (Digital Imaging and Communications in Medicine) file. DICOM is an industry standard for creating, storing, transmitting, and visualizing medical images and documents of examined patients.
Of the 224 patients included in the study, 125 were men (55.8%) and 99 were women (44.2%). The average age of patients in the general sample was 53.38±1.48 years. The average age of the men included in the study was 53.05±2.4 years, and the average age of the women was 53.98±2.06 years. The ratio of men to women in the study was 1:1.26. All patients enrolled in the study were divided into four age groups according to the World Health Organization (WHO) age classification: Group 1: young, from 20 to 44 years; Group 2: middle-aged, from 45 to 59 years; Group 3: elderly, from 60 to 74 years; and Group 4: senile, from 75 to 90 years.
Group 1 consisted of 34 people (20 men and 14 women). The average age was 34.7±6.5 years. Group 2 included 114 people (60 men and 54 women). The average age was 54.8±3.9 years. Group 3 included 64 people (37 men and 27 women). The average age was 64.8±3 years. Group 4 consisted of 12 people (eight men and four women). The average age was 81.8±5.9 years.
The WHO age classification is appropriate for studying portal vein anatomy because aging is associated with significant hemodynamic and structural changes in the portal venous system. Studies have demonstrated that portal blood flow parameters, including flow velocity and volume, peak in the mid-forties and decline significantly after 60 years of age [10]. These age-related changes occur due to progressive alterations in liver structure, including decreased hepatocyte number and size, morphological changes in sinusoidal vasculature, and loss of functional liver cell mass with advancing age [10]. Additionally, anthropometric parameters that correlate with portal vein diameter show age-dependent variations, making age stratification essential for establishing normative values [11].
The classification by Krumm et al. [8] was used to classify the portal vein confluence area (Fig. 1), according to which 10 types of confluence are distinguished:
Type A: The inferior mesenteric vein (IMV) flows into the splenic vein (SV).
Type B: The IMV is located in the corner of the confluence of the superior mesenteric vein (SMV) and the SV, which forms the portal vein.
Type C: The IMV flows into the SMV.
Type D: The accessory mesenteric vein (AccMV) enters the angle of confluence, as in type B.
Type E is similar to type A, with two equal trunks of the IMV and the AccMV. The IMV flows into the SV.
Type F is similar to type E. The IMV flows into the AccMV, which is equal in diameter to the SMV and flows into the angle of the SMV and SV confluence.
Type G is similar to type A, but the AccMV and the IMV flow into the SV simultaneously.
Type H: The IMV is missing.
Type I is similar to type A: the IMV flows into the SV, but there is an AccMV between the IMV and the SMV.
Type J: The IMV is equal in diameter to the SMV and flows into the angle of the confluence of the IMV and SV.

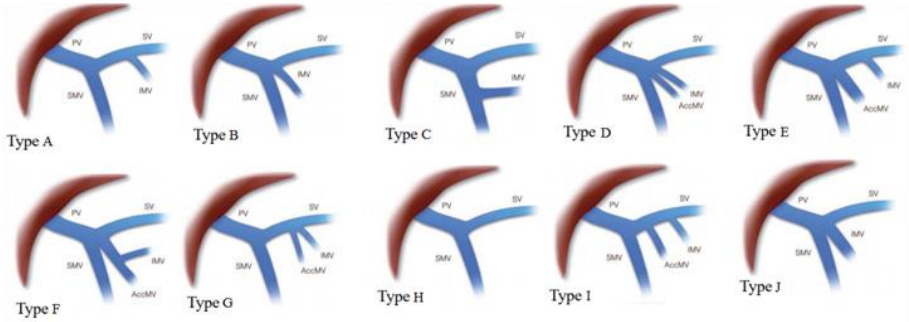


Fig. 1: Types of Portal Vein Confluence According to Krumm Et Al. Designations: PV Is the Portal Vein, SMV Is the Superior Mesenteric Vein, IMV Is the Inferior Mesenteric Vein, SV Is the Splenic Vein, and Accmv Is the Accessory Mesenteric Vein.

We used the classification developed by Nakamura et al. [9] to describe the variants of portal vein division (Fig. 2).
According to this classification, there are five variants of portal vein branching:
Type A is a classic variant of dividing the portal vein into right and left trunks.
Type B is the true trifurcation, without the main trunk of the right portal vein.
Type C is the extrahepatic transposition of the anterior branch of the right portal vein.
Type D is the intrahepatic transposition of the anterior branch of the right portal vein.
Type E is the transposition of individual segmental branches from the portal vein.

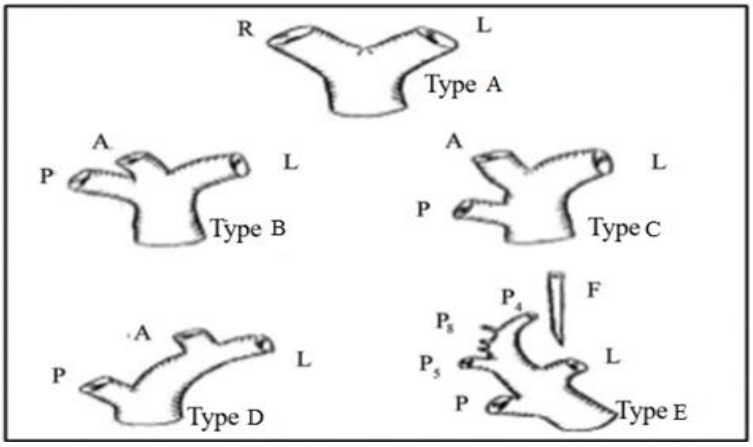


Fig. 2: Classification of Portal Vein Branching Variants.

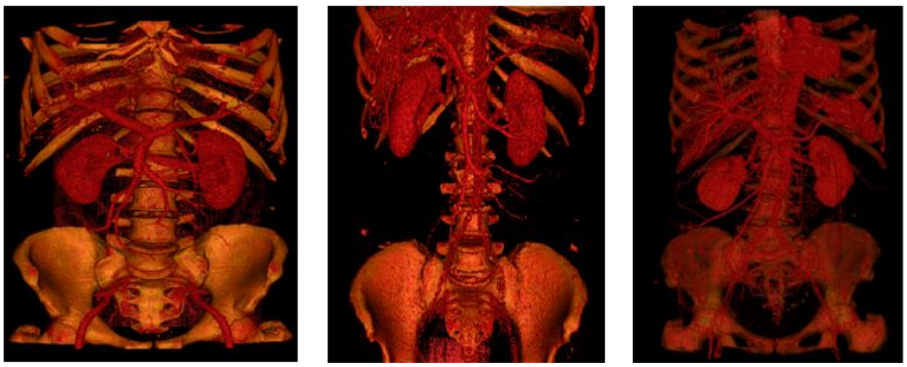
Note: compiled by authors according to Nakamura et al. [9]. Designations: L is the left branch, R is the right branch, A is the anterior right branch, P is the posterior right branch, and P4-8 are the segmental branches

All statistical analyses were performed using SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Categorical variables such as portal vein confluence types and branching patterns were summarized as frequencies and percentages. Differences across sex and age groups were evaluated using Pearson's chi-square (χ^2) test; when the expected cell frequency was below 5, Fisher's exact test was applied. The association between age group and portal vein variant type was additionally explored using the z-test for column proportions with Bonferroni correction. Numerical variables were compared between groups using the independent-samples t-test or one-way ANOVA where appropriate. All tests were two-tailed, and statistical significance was set at $p < 0.05$.

3. Results

In 224 patients who participated in the study, we identified seven different variants of portal vein formation. In the general sample, without considering the gender, the most common variant of portal vein formation, which significantly prevails over other variants, is confluence type A, in which the SV forms a common trunk with the IMV, which then connects to the SMV (Fig. 3a). In classical anatomical descriptions, this variant of the portal vein formation is considered typical. This type of portal vein confluence was detected in 102 out of 224 patients, or 45.5% of cases. In 26.8% (60 out of 224) of the observations, type B confluence was detected, in which the SMV, the SV, and the IMV connect at the same point (Fig. 3b). 16.5% (37 out of 224) of the observations detected type C confluence, in which the IMV forms a common trunk with the SMV, which then connects to the SV (Fig. 3b). The three portal vein formation variants described above collectively account for 88.8% of the observations. In absolute terms, this is 199 out of 224 patients. These confluence variants are characterized by the confluence of the three main roots of the portal vein. The anatomy of the SMV and the SV is relatively constant, while the anatomy of the IMV is characterized by significant variability of the confluence site.

In 6.7% (15 out of 224) of the observations, the AccMV forms the portal vein in addition to the three main roots. Three variants of portal vein formation with the participation of the AccMV were identified. Thus, in the general sample, 3.6% (8 out of 224) of observations showed type D confluence, in which the AccMV and IMV enter the angle of the SMV and the SV confluence. In 2.2% (5 out of 224) of the observations, type E confluence was detected, in which the inferior mesenteric and AccMVs have equal diameters. At the same time, the IMV flows into the SV as in type A confluence, and the accessory vein flows into the angle of the SMV and SV confluence. In 0.9% (2 out of 224) of the observations, type G confluence was detected (the confluence of the AccMV and IMV into the SV at the same point). In 4.5% (10 out of 224) of the 10 observations, the absence of the IMV (confluence type H) was shown. In this case, the portal vein was formed by the confluence of the SMV and the SV.



a b c

Fig. 3: Three-Dimensional Reconstructions of Portal Vein Confluence Variants.

Note: compiled by authors according to Krumm et al. [8]: (a) Type A – the inferior mesenteric vein (IMV) drains into the splenic vein (SV); (b) Type B – the IMV enters at the angle of confluence between the superior mesenteric vein (SMV) and the SV; (c) Type C – the IMV joins the SMV before their union with the SV. PV = portal vein.

In both men and women, the vast majority of cases occur in three types of confluence: type A (confluence of the SMV and the common trunk of the SV and the IMV), type B (confluence of the SMV, the SV, and IMV at the same point), and type C (confluence of the SV and

the common trunk of the IMV and the SMV). These variants account for 91.2% (114 out of 125) of observations in men and 85.8% (85 out of 99) of observations in women. In the general sample of both men and women, confluence type A is significantly predominant ($p < 0.01$). This type of portal vein formation was detected in 60 out of 125 men, or 48%. In women, type A portal vein confluence was detected in 42.4% (42 out of 99) of cases. Portal vein type B confluence was detected in 24.8% (31 out of 125) of men and 29.3% (29 out of 99) women. Type C confluence in men was detected in 18.4% (23 out of 125) cases and women in 14.1% (14 out of 99) cases.

The formation of the portal vein with the participation of the AccMV was detected more often in women than in men. Thus, in men, the AccMV was detected in 4.8% of cases or 6 out of 125 men, and two variants of portal vein formation with the participation of the AccMV were identified. Three men, or 2.4% of the cases, showed type D confluence (the confluence of the AccMV along with the IMV into the angle of the confluence of the SMV and SV). In three men or 2.4% of cases, the confluence of the portal vein type E was detected (the AccMV flows into the angle of the confluence of the SMV and the SV, and the IMV flows into the SV). In women, the AccMV was detected in 9.1% of cases, or 9 out of 99 women. Women also had more variants for the formation of the portal vein with the participation of the AccMV. Five women, or 5.1% of the cases, had type D confluence. Two women, or 2% of the cases, showed type E confluence. Finally, two women (2% of cases) had type G confluence (the AccMV and IMV confluence into the SV at the same point). The absence of the IMV (confluence type H) was detected in five men (4% of cases) and five women (5.1% of cases). We did not identify any significant differences in the frequency of confluence variants related to gender.

A detailed statistical comparison confirmed the predominance of type A confluence across the entire cohort ($\chi^2 = 9.71$, $p = 0.008$). No significant association was found between sex and confluence type ($\chi^2 = 4.13$, $p = 0.39$), or between age group and confluence type ($\chi^2 = 7.25$, $p = 0.29$). Similarly, no significant gender difference was observed in portal vein branching variants ($\chi^2 = 2.84$, $p = 0.42$). The z-test for column proportions, with Bonferroni correction, confirmed that the prevalence of the classical type A division (71.9%) was significantly higher than that of type B (20.1%) and type C + D combined (8.0%) ($z = 4.23$, $p < 0.001$). Mean portal-trunk angle values did not differ between men and women ($t = 0.57$, $p = 0.57$) or among age groups (ANOVA $F(3,220) = 1.12$, $p = 0.34$).

We used the classification by Nakamura et al. [9] to describe the variants of portal vein division. According to this classification, four types of portal vein branching were identified. The classical type of portal vein division into right and left trunks (type A) in the general sample, not considering gender, was detected in 161 of 224 patients, or 71.9% of cases. In 20.1% (45 out of 224) of the observations, a true trifurcation of the portal vein was found without the main trunk of its right branch (type B). These two variants of portal vein division are the most frequent and were detected in 92% (206 out of 224) of the general sample. The remaining atypical types of portal vein branching were much less common. Thus, in 4.9% (11 out of 224) of the observations, extrahepatic transposition of the anterior branch of the right portal vein (type C) is determined. 3.1% (7 out of 224) of the observations detected intrahepatic transposition of the anterior branch of the right portal vein (type D). None of the patients we examined had a type E portal vein division (lacking a complete branch of the anterior right portal vein).

We established that the type A portal vein division, as defined by Nakamura et al. [9], i.e., its typical dichotomous division into right and left branches, is significantly predominant in both men and women ($p < 0.01$). This division occurs in 71.2% (89 out of 125) of cases in men and 72.7% (72 out of 99) of cases in women. Portal vein trifurcation (type B portal vein division) in men was detected in 20.8% (26 out of 125) of cases and women in 19.2% (19 out of 99) of cases. Extrahepatic transposition of the anterior branch of the right portal vein (type C portal vein division) in women is observed in 8.1% (8 out of 99) cases. Type C portal vein division was observed less frequently in men than women. This type of portal vein branching in men is observed in 2.4% (3 out of 125) cases. Intrahepatic transposition of the anterior branch of the right portal vein (type D portal vein division) in men was detected in 5.6% of cases (seven observations). No cases of portal vein type D division were identified in women. Type E portal vein division (absence of a complete branch of the anterior right portal vein) was not found in either men or women in the study. Differences in the frequency of portal vein branching of types A, B, and C based on gender are not statistically significant. Type D portal vein division is significantly more common in men ($p=0.017$).

When studying the variant of portal vein division depending on the type of its formation, we found that in patients with such variants of portal vein formation as type A (confluence of the SMV at the common trunk of the SV and IMV), type B (confluence of the roots of the portal vein at the same point), and type C (confluence of the SV and the common mesenteric trunk) the typical division of the portal vein into right and left branches (type A division) significantly prevailed.

In 75 out of 102 patients with type A confluence, or 73.5% of cases, the portal vein had division type A (bifurcation into right and left branches), division type B (trifurcation of the portal vein) in 18.6% (9 out of 102) of cases, and division type C (extrahepatic transposition of the anterior branch of the right portal vein) in 7.9% (8 out of 102) of cases. Four variants of portal vein division were identified in 60 patients with type B portal vein confluence. In 75% (45 out of 60) of the observations, the portal vein had division type A, in 16.7% (10 out of 60) of the observations it had division type B, in 5% (3 out of 60) of the observations it had division type C, and in 3.3% (2 out of 60) of the observations it had division type D (intrahepatic transposition anterior branch of the right portal vein). Only two types of portal vein division were observed in 37 patients with the type C portal vein confluence. In 75.7% (28 out of 37) of the observations, the portal vein had division type A, and 24.3% (9 out of 37) had division type B.

During the formation of the portal vein with the participation of the AccMV (D, E, and G confluence types) and in the absence of the IMV (type H confluence), not a single case of typical division of the portal vein into the right and left branches was observed. With these types of portal vein formation, the predominant variant of portal vein branching was its trifurcation (type B). In eight patients with type D confluence (confluence of the AccMV with the IMV into the angle of confluence of the SMV and SV, in 62.5% (5 out of 8) of cases, the portal vein was of division type C, and in 37.5% (3 out of 8) of cases, it was of division type D. In five patients with type E confluence (the AccMV flows into the angle of confluence of the SMV and SV, and the IMV flows into the SV), the portal vein had a type B division in all cases. In type G confluence (confluence of the AccMV and the IMV into the SV at the same point), which was observed in two patients, in one case, the portal vein had division type B, and in the second case, it had division type D. In 10 patients with type H confluence, the portal vein had division type B in 60% (6 out of 10) of cases, division type C in 30% (3 out of 10) of cases, and division type D in 10% (1 out of 10) of cases.

4. Discussion

Future studies should investigate whether specific anatomical variants of the portal vein are associated with increased risk of postoperative complications following hepatobiliary surgery. Recent advances in three-dimensional visualization have revealed that portal vein anatomical variants are more common than previously reported, with some classification systems identifying up to 13 distinct subtypes [12]. This growing complexity suggests that machine learning algorithms could be developed to automatically recognize and classify portal vein anatomy from CT imaging data, potentially improving preoperative planning accuracy and reducing inter-observer variability.

Additionally, prospective multicenter studies are needed to establish standardized protocols for reporting anatomical variants and their clinical significance. Such research could help surgeons better anticipate technical challenges and select optimal surgical approaches based on individual patient anatomy.

In the classical description, the main roots of the portal vein are the SMV and the SV, which form a single trunk with the IMV. According to the classification developed by Krumm et al., this corresponds to type A confluence. The frequency of portal vein confluence's classical variant varies significantly according to the literature data. According to various authors, it occurs with a frequency ranging from 28% to 72%. Thus, in the study by Purcell et al. [13], the confluence of the inferior portal vein into the SV occurred in 28% of the observations, and in the studies by Raut [14] and Krumm et al. [8], in 30% and 37.6%. Khamanarong [2] and Gaivoronskii [15] encountered type A confluence in 55.5% and 72%, respectively.

The frequency of atypical portal vein formation variants also varies markedly. According to Purcell, Khamanarong, and Gaivoronskii, the variant of the IMV's confluence into the SMV is more common, while Krumm and Raut indicate a more frequent confluence of the IMV in the angle of the confluence of the SMV and SV. In the study by Purcell, type B confluence prevailed and was found in 53% of observations, while type C confluence was found in 3% of observations. Khamanarong and Gaivoronskii note the predominance of type A confluence in their works. According to Khamanarong, the frequency of type B and C confluences is 43.13% and 1.42%, while according to Gaivoronskii, it is 22.30% and 4.7%. Krumm notes the predominance of type C confluence compared to type B confluence. According to Krumm, the indicated confluence variants are found in 19.2% and 28.8%, respectively. Raut names the confluence of the IMV into the SMV (type C confluence) as the most common variant, occurring in 47.5% of observations. According to Raut, type B confluence occurs in 20% of observations.

According to the classification by Nakamura et al. [9], our study showed four variants of portal vein branching. The variant of portal vein division, which is dichotomously divided into independent right and left branches and the right branch is divided into right anterior and right posterior branches, is considered a normal variant of portal vein division. Data on the frequency of occurrence of this variant of portal vein division vary significantly. Atrevi [16] indicates a frequency of occurrence of 31.25%. In our study, a typical portal vein division occurred in 71.9% of cases. Our data are close to those obtained by Cheng [17], who identified portal vein bifurcation in 70.9% of observations. Despite the marked difference in data, all authors agree that the typical variant of portal vein branching is predominant.

We found that portal vein trifurcation was the most common of the atypical variants, as confirmed by most authors [18]. Such a variation was detected in 20.1% of observations, which is close to the data of Ayad [19] (26% of observations). Extrahepatic and intrahepatic transposition of the anterior branch of the right portal vein was detected in 4.9% and 3.1% of cases. Our data are close to the results by Nakamura et al. [9], who identified these portal vein division variants in 2.5% and 1.7% of observations. In Covey [20], extrahepatic transposition was detected in 13% of cases and was the most common variant of atypical portal vein branching. Atasoy [21] indicates the predominance of the right portal vein's anterior branch among atypical intrahepatic transposition variants. Atasoy detected this variant of portal vein branching in 13% of the observations.

The wide variations in frequencies of portal vein confluence and branching type might be the result of differences in methodology and study population. In cadaveric studies on the anatomy of the portal vein, the frequency of confluence and branching types may be affected by postmortem changes, sample shrinkage and incomplete filling. The increased detection of atypical variants in more recent literature may also be due to the improved spatial resolution and in vivo assessment of modern multidetector CT and 3D reconstruction techniques. Other studies have reported variations in the portal vein configuration as population specific, with factors including ethnicity and anthropometry of patients playing a role. Protocol standardization for imaging and classification across studies would improve inter-study comparability and data reproducibility.

5. Conclusion

Knowledge about the portal vein formation variant is necessary when planning surgical interventions on the organs of the hepatobiliary system. Thus, in the case of atypical portal vein confluence, portocaval or splenorenal bypass surgery may be complex. The variability of the confluence zone creates many problems for surgeons during pancreatoduodenectomy. During pancreas resection, resection of the portal vein may be required. The anatomical variants of the portal vein roots may determine the options for venous reconstruction, which dictates the thoroughness of studying the confluence variant at the stage of preoperative preparation.

The portal vein's variant anatomy plays an essential role in planning liver surgery, and atypical variants of portal vein branching can significantly affect the surgeon's tactics. Thus, when the individual segmental branches depart directly from the portal vein, the caliber of the right branch of the portal vein does not allow for successful intervention. During portal vein embolization, extrahepatic transposition of the anterior branch of the right portal vein complicates the procedure, and a curved catheter is required to embolize the 5th and 6th segmental branches. When planning a related liver transplant, it is important to be aware of the presence of portal vein trifurcation due to the high risk of intraoperative branch intersection and the development of massive bleeding. The portal vein branching variant is critical when choosing the portal reconstruction options for liver fragment transplantation from a living related donor and split transplants. Thus, the portal vein's trifurcation can significantly complicate a portal anastomosis's imposition.

Ethics Approval and Consent to Participate

This study was conducted in accordance with the principles of the Declaration of Helsinki. Ethical approval for the use of anonymized MSCT data was obtained from the Ethics Committee of Samara State Medical University no. 04-2025 in April 2025.

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