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REVIEW ARTICLE

VASCULAR LIVER ANATOMY AND MAIN VARIANTS: WHAT THE RADIOLOGIST MUST KNOW

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Advances in surgical techniques are extremely demanding regarding the accuracy and level of detail expected for display of the vascular anatomy of the liver. Precise knowledge of the arterial, portal and hepatic vein territories are mandatory whenever a liver intervention is planned. Sectional anatomy can now be routinely performed on multidetector computed tomography (MDCT) with volumetric data and isotropic voxel display, by means of sub-millimetric slice thickness acquisition. The relevant vascular information can thus be gathered, reviewed and post-processed with unprecedented clarity, obviating the need for digital subtraction angiography. The scope of the present paper is to review the normal vascular liver anatomy, its most relevant variants including additional sources of vascular inflow. Apart from providing the surgeon with a detailed vascular and parenchymal roadmap knowledge of imaging findings may avoid potential confusion with pathologic processes.

Key-word: Liver, anatomy.

Despite refinements in liver surgical techniques, particularly microvascular reconstructions, vascular complications still account for considerable morbidity and mortality. Presurgical planning of vascular anastomosis and variations is a key component for a variety of liver surgeries, including transplantation, tumor resection, and laparoscopic hepatobiliary surgery (1). Detailed knowledge of the hepatic angioarchitecture is thus considered a prerequisite for successful, uncomplicated liver surgeries (1-3). The goals are to choose the best therapeutic approach, to reduce complications, and to identify the anatomy requiring special attention at surgery.

From the various sectional imaging techniques undoubtedly multidetector computed tomography (MDCT) providing high spatial and temporal resolution is at the forefront of the evaluation of vascular liver anatomy (4, 5). Therefore, the aim of this paper is to review and illustrate the normal anatomy and main variants of the hepatic vasculature using MDCT with advanced post-processing algorithms, as well as to review current concepts of liver segmentation (VR) (6, 7).

Table I. Michels' classification of hepatic arterial anomalies

Type	Description	Prevalence (%)
I	Normal anatomy	55
II	Repl. LHA from LGA	10
III	Repl. RHA from SMA	11
IV	Repl. LHA from LGA and repl. RHA from SMA	1
V	Acc. LHA from LGA	8
VI	Acc. RHA from SMA	7
VII	Acc. LHA from LGA and acc. RHA from SMA	1
VIII a)	Acc. LHA from LGA and repl. RHA from SMA	2
VIII b)	Repl. LHA from LGA and acc. RHA from SMA	2
IX	CHA from SMA	4.5
X	CHA from LGA	0.5

LHA left hepatic artery, LGA left gastric artery, RHA right hepatic artery, SMA superior mesenteric artery, CHA common hepatic artery, Repl. replaced, Acc. Accessory.

Arterial anatomy

The anatomy of the hepatic artery and its variants has been widely described in the literature especially provided by large autopsy series (8-13). Variants are seen as developmental changes of the primitive ventral splanchnic arteries. All the classical variations can consequently be explained by the abnormal disappearance of an arterial segment that should normally persist, persistence of an arterial segment that should disappear, or both.

An aberrant hepatic artery refers to a branch that does not arise from its usual origin. The liver may receive blood supply directly from the superior mesenteric artery (SMA), left gastric artery (LGA), aorta, or other visceral branches corresponding to a complete transposition. However, these vessels may be accessory, meaning that they add on to the normal arterial supply which still represents the primary arterial supply to the liver.

In Michels' classic autopsy series of 200 dissections, published in 1955 (10), the basic anatomical variations in hepatic arterial supply were defined and this classification has served as the benchmark for all subsequent contributions in this area (4, 14-17). Michels described 10 types of configuration for the hepatic vasculature, including the normal configuration (Table I). Type I anatomy, consists of the common hepatic artery arising from the celiac trunk, from

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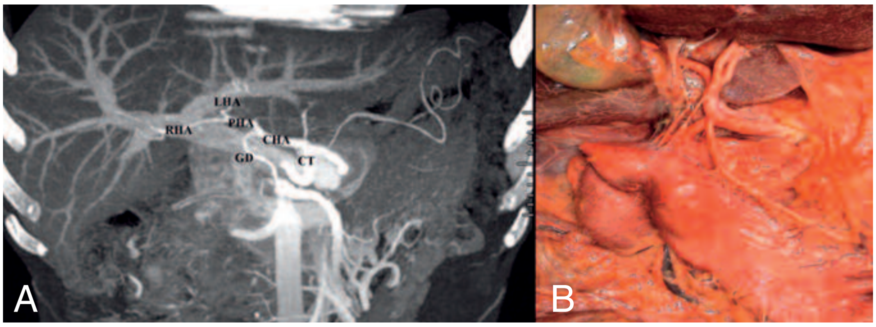

Fig. 1. — Normal hepatic arteries. Coronal thick slab MIP image (A) and cadaveric dissection (B). The common hepatic artery (CHA) arises from the celiac trunk (CT). After giving rise to the gastroduodenal artery (GD), it continues as the proper hepatic artery (PHA), which divides into right hepatic artery (RHA) and left hepatic artery (LHA).

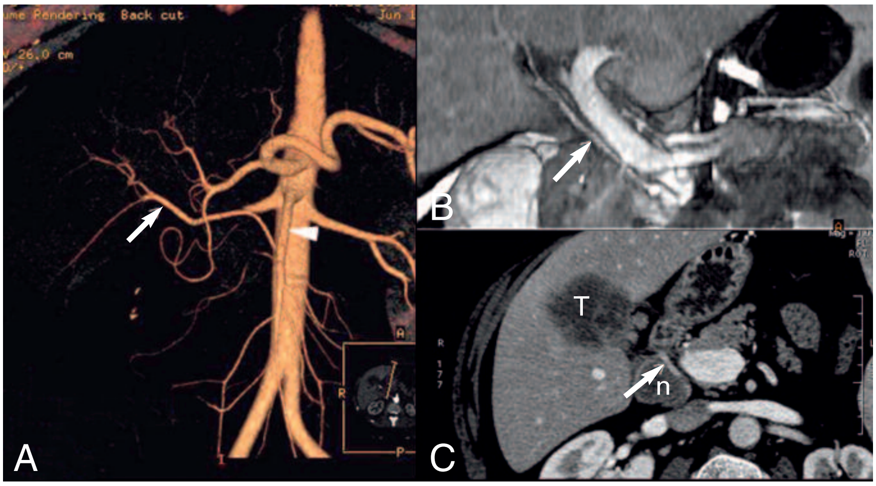

Fig. 2. — Michels' type III anatomy. A: VR image. The right hepatic artery (arrow) arises from the superior mesenteric artery (arrowhead). B: VR image. C: Axial CT. When the right hepatic artery arises (arrow) from superior mesenteric artery it runs upwards behind the pancreas and dorsal to the portal vein in the portocaval space. On C an invasive gallbladder tumour (T) and a mestastatic node (n) are seen.

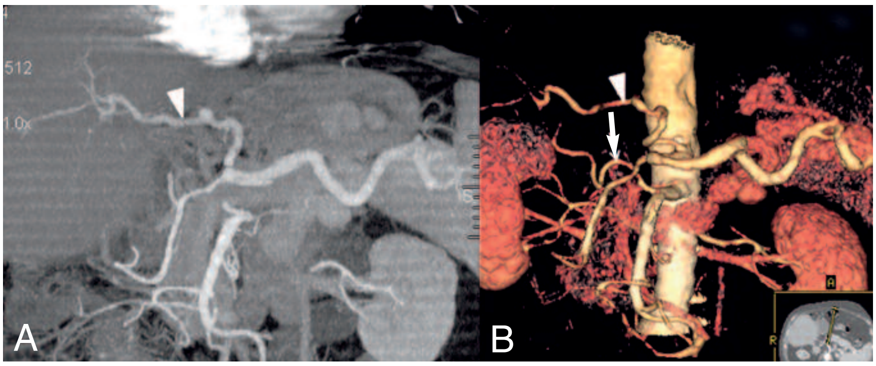

Fig. 3. — Michels' type IV anatomy. A: Thick slab coronal MIP image. B: VR image. The right hepatic artery (arrow) arises from the superior mesenteric artery and the left hepatic artery (arrowhead) arises from left gastric artery.

which the gastroduodenal artery and the proper hepatic artery arise (Fig. 1). The proper hepatic artery branches off the right hepatic artery (RHA) after the left hepatic artery (LHA). Further on RHA splits into its anterior and posterior branches and the LHA splits to feed segments II and III. Segment IV is fed by one or more branches originating from the LHA, RHA, or both. The frequency of occurrence of normal hepatic arterial anatomy ranges between 55-76% (4, 18-19). In the type II Michels' variant the LHA originates from the left gastric artery (LGA). The replaced artery can be seen running through the lesser sac entering the liver via the fissure for the ligamentum venosum, into the umbilical fissure. This is the second most common arterial variant, occurring with a frequency of 10%.

In the type III Michels' variant the RHA branches off from the SMA (Fig. 2). Whereas the right hepatic artery usually courses anterior to the right portal vein, the replaced right hepatic artery, runs posterior to the main portal vein in the portocaval space, and classically ascends posterolateral to the common bile duct. This is the most common variant accounting for 11% of cases. Type IV Michels' variant corresponds to a situation where type II and type variants III coexist: both lobar arteries are replaced with the RHA originating from the SMA and the LHA from the LGA (Fig. 3). This kind of variant is rare with a reported incidence of only 1%. The remaining types of this classification are described in table 1. For illustrative purposes two different cases of type VIII (Fig. 4) and IX (Fig. 5) are shown attending to their rarity accounting for 2 and 0.2% of all arterial variants, respectively. It should be stressed that other variants, not included in the original Michels's classification have also been described such as a replaced RHA or the common hepatic artery originating directly from the aorta. Of special interest is the anatomy of the artery (or arteries) that feed segment IV, because of its importance for surgical procedures involving this specific segment such as the case of left liver donors for liver transplant in pediatric patients. Its configuration is quite variable and it is possible to observe a single, double, and triple supply, originating from RHA, LHA and/or proper hepatic artery (Fig. 6) . Usually the segment IV artery originates from the LHA in 64-75% of patients and from the RHA in 25% corresponding to what has been coined as the vascular arcade (5, 18, 20).

Portal venous anatomy

The portal vein is formed in the retroperitoneum by the confluence of the superior mesenteric vein and the splenic vein, behind the neck of the pancreas and courses behind the duodenal bulb. In its most common branching pattern it divides at the porta hepatis into right and left portal veins (Fig. 7). The portal bifurca-

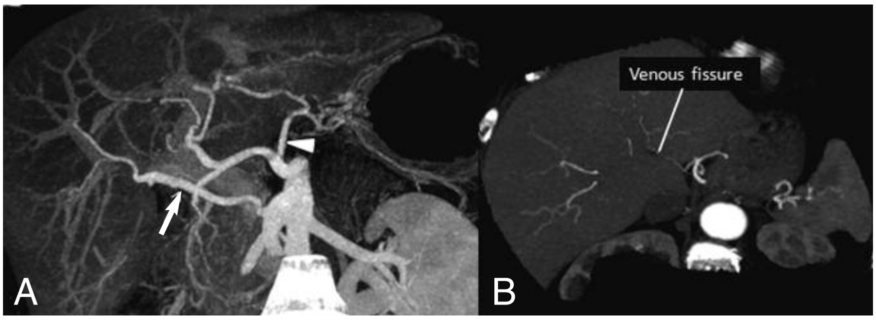

Fig. 4. — Michels' type VIII anatomy. A: Thick slab MIP. The replaced right hepatic artery (arrow) arises from the superior mesenteric artery and there is an acessory left hepatic artery (arrowhead) that arises from the left gastric artery. B: Whenever the left hepatic artery arises from the left gastric artery it runs in the lesser omentum and enters the liver via venous fissure.

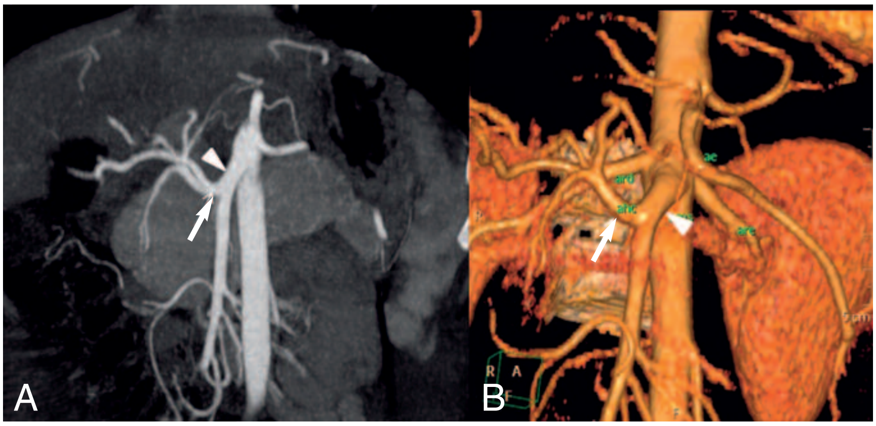

Fig. 5. — Michels' type IX anatomy. A: MIP image. B: VR image. The main hepatic artery (arrow) originates from the superior mesenteric artery (arrowhead).

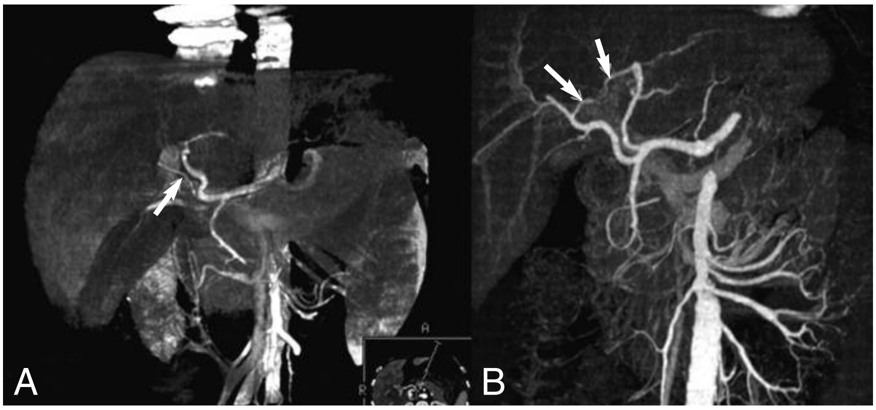

Fig. 6. — Segment IV artery. A: VR image. The middle hepatic artery (arrow) originates from proper hepatic artery. B: MIP image. In this case there is a double supply for segment IV (arrows), one branch originating from the left hepatic artery and the other branch from the right hepatic artery.

tion may be extrahepatic (48% of cases), intrahepatic (26%), or located right at the entrance of the liver (26%) (21, 22).

As it courses cranially, the right portal vein first gives off collateral branches to the caudate lobe and then divides into anterior and posterior branches, which further subdivide into superior and inferior segmental branches to supply the right lobe of the liver. The left portal vein first has a horizontal course (pars horizontalis) to the left and then turns medially toward the ligamentum teres (pars umbilicalis, ie, the vertical part), supplying the lateral segments (segments II and III) of the left lobe. It displays a wide anterior concavity ending up at the superior and inferior segmental branches of segment IV. The segmental veins divide into subsegmental branches, and further on into small veins abutting at the portal triad at the level of the liver acinus.

Branching anomalies of the main portal vein (PV) at the hepatic hilum are known to be less frequent (10-20% of cases) than those of the hepatic arteries and hepatic veins (23-26). Embryologically, the PV is formed during the second month of gestation by selective involution of vitelline veins, which have multiple bridging anastomoses, both anterior and posterior to the duodenum. Modifications in the pattern of these anastomoses end up in PV variations.

According to the literature (25-27), the most common patterns are represented by: a) trifurcation of the main portal vein (7.8%-10.8%); in these cases, the main portal vein divides into three branches after entering the porta hepatis; a right anterior segment, a right posterior segment, and a left portal vein (Fig. 8); b) origin of the right posterior segmental branch directly from the main portal vein (4.7%-5.8%), where the main portal vein gives rise to the right posterior segment, then continues to the right for a short distance, and divides into the right anterior segmental branch and the left portal vein; c) origin of the right anterior segmental branch from the left portal vein (2.9%-4.3%); in these cases, the main portal vein divides into the right posterior segment and the left portal vein. The right anterior segmental vein originates from the left portal vein (Fig. 9).

Less well defined variations of the "normal" distribution of portal vein are commonly seen. These include a short main right portal vein, a short horizontal portion of the left portal vein, disproportionate size of different segmental branches, and a small accessory branches (arising from the main portal vein) to the right posterior segment. Some of the latter variations correlate with differences in the size of some segments of the liver, where a hypoplastic segment receives small branches.

There may be cases of congenital absence of the portal vein, where all the blood carried by the superior mesenteric and splenic veins bypasses the liver draining directly into a systemic vein. This congenital

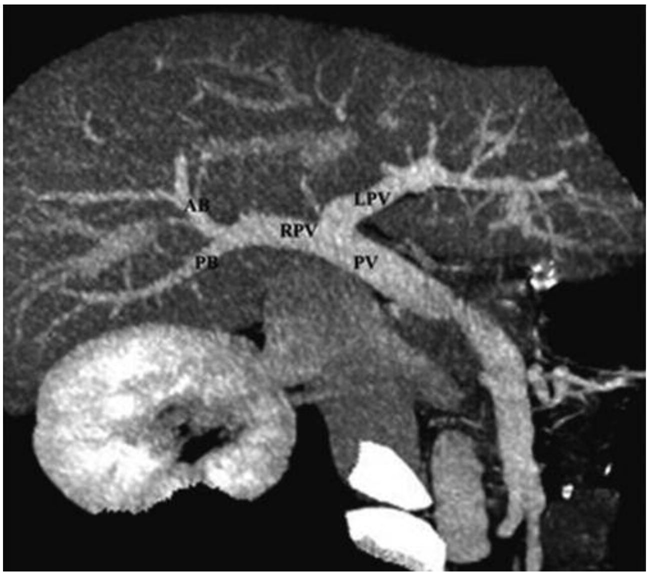

Fig. 7. — Normal portal vein anatomy. MIP image. The main portal vein (PV) divides into right portal vein (RPV) and left portal vein (LPV). The RPV bifurcates into anterior branch (AB) and posterior branch (PB), both of which bifurcate into ascending and descending branches. Each of these four branches supplies a segment of the right lobe. The left portal vein (LPV) divides into three branches, one for each segment of the left lobe.

Fig. 8. — Portal vein trifurcation. MIP image. Main portal vein (PV) divides into right anterior (AB) and posterior (PB) branches and left portal vein (LPV). A right portal vein is not identified.

Fig. 9. — Right anterior segmental branch arising from the left portal vein. MIP image. There is an absence of the right branch of the portal vein. The portal vein (PV) bifurcates into a left and posterior branch (to segments VI and VII). The anterior branch (arrow) to segments V and VIII arises from the left branch of the portal vein (LPV).

Fig. 10. — Congenital absence of the portal vein. The splanchnic vein joins the inferior vena cava forming a porto-systemic congenital shunt (arrow). Note a large macroregenerative nodule (asterisk) secondary to the perfusion abnormality of the liver.

malformation was first described by Abernathy in 1793 and is a clear example of a portosystemic shunt (Fig. 10).

Morgan and Superina (28) subsequently refined the classification of portal shunting into two different types: type I, when all portal venous blood is shunted to a systemic vein, with complete bypass of the liver (e.g. congenital absence of the portal vein). This type of shunt has been referred to as a 'total' shunt or 'end/side' shunt; type II shunt when only a portion of the portal venous flow is diverted from the liver corresponding to a 'partial' shunt or a 'side/side' shunt.

Hepatic veins anatomy

The three main hepatic veins (right, middle, and left) drain into the inferior vena cava (IVC) approximately 1 cm below the diaphragm and 2 cm inferior to the lower border of the right atrium (Fig. 11). The right hepatic vein (RHV) is the one widest since it drains a larger volume of liver parenchyma (segments V-VIII). The middle hepatic vein (MHV) runs along the main portal fissure draining segments IV, V and VIII. The left hepatic vein (LHV) drains segments II and III and generally forms a common trunk with the middle hepatic vein (MHV) in 85% of cases, ulti-

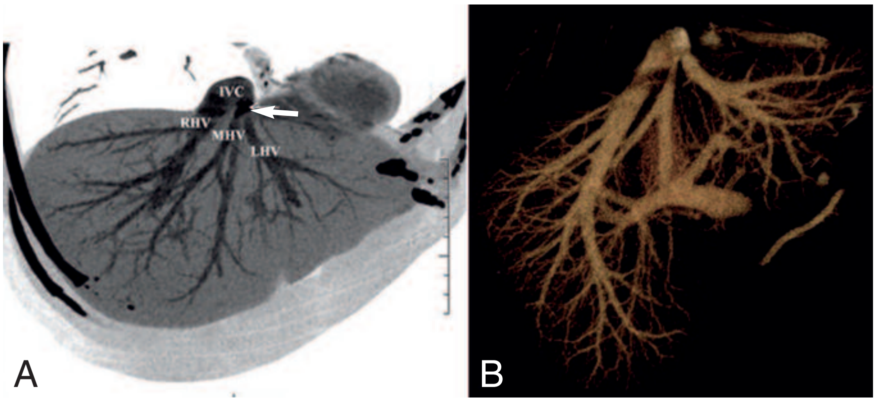

Fig. 11. — Normal hepatic veins. A: MIP image. B: VR image. Normal hepatic veins, usually consisting of three main hepatic veins: right hepatic vein (RHV), middle hepatic vein (MHV) and left hepatic vein (LHV). The LHV forms a common trunk (arrow) with the MHV in 85% of cases.

Fig. 12. — Accessory hepatic vein (arrow). MIP image. They are significant for surgical purposes when their diameter is superior to 5mm.

mately draining into the anterior left lateral aspect of the IVC (29,30). The LHV is the smallest of these veins. Segment I has its own venous drainage directly into the inferior vena cava via a variable number of independent veins.

The anatomy of the major hepatic veins is quite variable. Also smaller accessory veins (AHVs) may be recognized, draining into the retrohepatic portion of the inferior vena cava between the right adrenal vein and the confluence of the main hepatic veins. These veins lack a precise systematization except for the accessory vein of segment VI, the largest and well recognized of all. AHVs are small and numerous, but their clinical relevance for liver surgery, should only be acknowledged when its diameter exceeds 5 mm (Fig. 12). However, their pathophysiologic importance may be greater when the venous drainage of the liver is compromised, such as in Budd-Chiari syndrome or in cases of large central tumors of the liver.

An accessory RHV occurs in 52.5% of patients (Fig. 13), two accessory hepatic veins in 12%, and a dominant accessory vein draining the caudate lobe in 12%.

The most frequent variations found in literature are (31): a) a dominant right accessory hepatic vein seen in 3-5% of patients, which is larger in caliber than the right hepatic vein (which may be atretic or even absent in such a case); b) absence of a common trunk formed by the middle and the left hepatic veins; c) The vein that drains the liver near the falciform ligament is a tributary of the middle hepatic vein instead of the left hepatic vein.

Also of paramount importance is the recognition of the territories of liver drainage of the hepatic veins. This has major implications in the context of liver donor liver transplant (LDLT) procedures where segmental territories may be deprived of their venous drainage ending up in venous congestion and reducing the final graft volume (Fig. 14) (32).

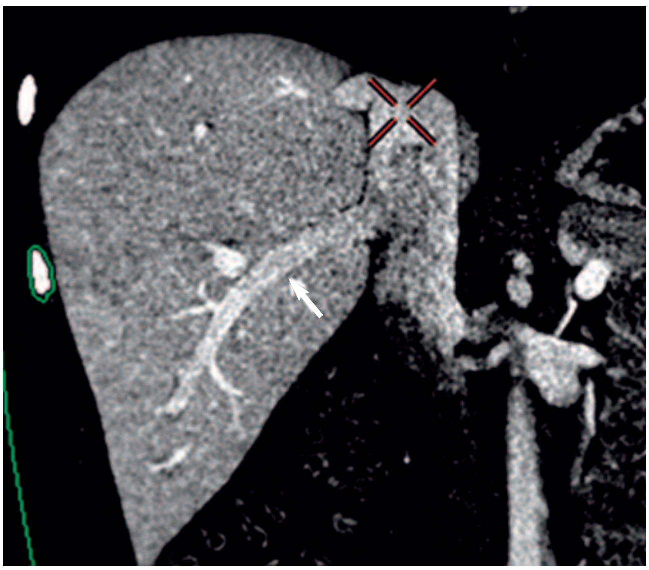

Fig. 13. — Large accessory right hepatic vein (arrow), draining segment VI.

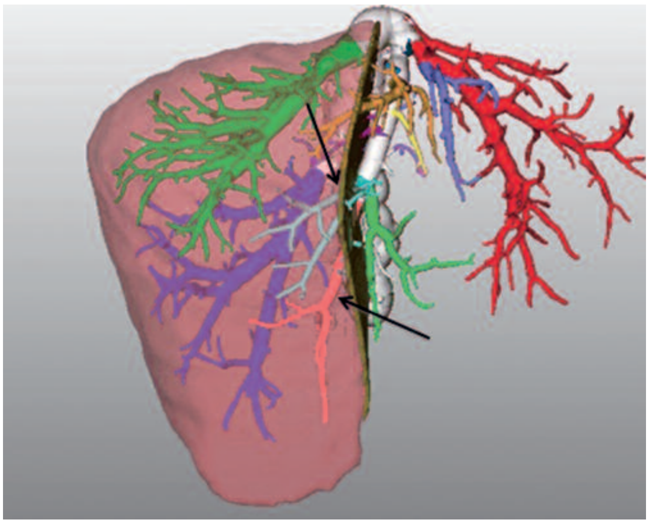

Fig. 14. — Advanced liver segmentation in the context of liver donor liver transplant. Portions of the right liver lobe are drained by the middle hepatic vein (arrows). This should be known beforehand since it may modify surgical planning (areas at risk for passive congestion if middle hepatic vein is transposed to the donor).

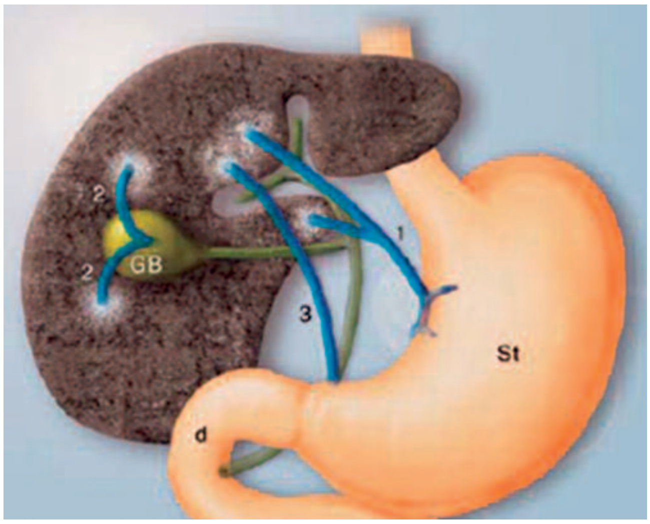

Fig. 15. — Schematic drawing of non-portal splanchnic perfusion to the liver parenchyma . 1 - aberrant gastric vein drainage to segments I and IV. 2 - cystic veins to segments IV and V. 3 - parabiliary venous system to the posterior aspect of segment IV. GB, gallbladder; ST, stomach; d, duodenum. According to Caseiro-Alves F, Ferreira A, Mathieu D. Focal Liver Lesions, Berlin, 2005, Springer. Chapter 11:160

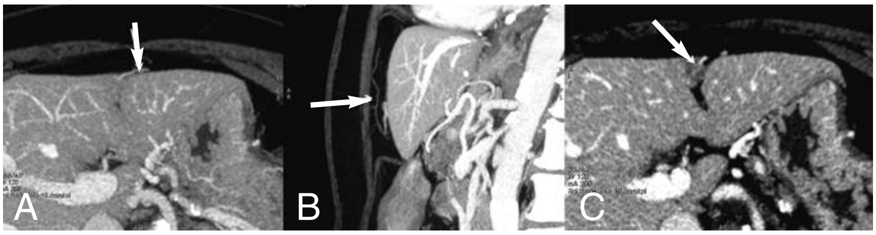

Fig. 16. — Veins of Sappey. A: Axial MIP. B: Sagittal MIP. Veins of Sappey are small veins (arrows) that drain into hepatic parenchyma around falciform ligament and are part of epigastric-paraumbilical venous system. C: These veins are responsible for perfusion and steatosic disorders (arrow) around falciform ligament.

Non-portal venous supply to the liver

In some instances, veins draining digestive organs do not flow into the portal vein trunk, but instead abut directly into the liver parenchyma. These anatomical variations have been consistently reported, and angiographically demonstrated. This is the case for a cystic vein draining directly from the gallbladder into segments IV-V, the parabiliary venous system draining the pancreatic head, duodenum and distal stomach into the posterior aspect of segment IV and the aberrant gastric venous drainage coming from the gastric antrum and pancreatic head draining directly into segments I and IV (Fig. 15) (33). On dynamic contrast-enhanced CT/MR the liver areas receiving this venous drainage may show early enhancement due to earlier venous return of less diluted contrast agent when compared with the portal blood flow coming from the intestine and spleen. Another consequence derives from the fact that the blood conveyed by these third inflow tracts to the liver do not carry the lipotrophic factors and hormones (especially insuline) normally present in the portal flow and coming from the intestinal circulation. This may lead to focal parenchymal abnormalities such as fatty sparing and focal fatty infiltration (Fig. 16).

Apart from the vascular variants other third inflow tracts feeding areas of liver parenchyma via direct connection with the systemic venous system may arise. This is the case represented by the superior vena cava obstruction leading to a network of collateral circulation between the thorax and the abdomen by intermediate of intercostal veins, internal mammary, hemiazygos and paravertebral veins. These systemic veins can end deeply in the umbilical vein, in the left portal vein or enter the left liver lobe directly by the paraumbilical inferior veins of Sappey (Fig. 16) (34). This explains the dense parenchymal staining, that may be seen in the early phases of liver enhancement near the round ligament, the left portal vein or in more remote subcapsular areas, corresponding to the early arrival of a considerable amount of minimally diluted contrast agent to these areas of liver parenchyma (35). The parenchymal staining may be so intense that mimics a true hypervascular neoplasm (Fig. 17).

Functional liver territories

Liver anatomy can be described using two different concepts: morphological anatomy and functional anatomy. The gross description of the external liver anatomy does not take in account vessels and biliary ducts branching, which are of obvious importance for hepatic surgery. As an example, the quadrate lobe although belonging to the anatomical right lobe of the liver, is functionally dependent of the left lobe.

Description of functional liver anatomy was initiated by Cantlie in 1898 and was followed by works of Healey and Schroy (36), Goldsmith and Woodburne (37), and more

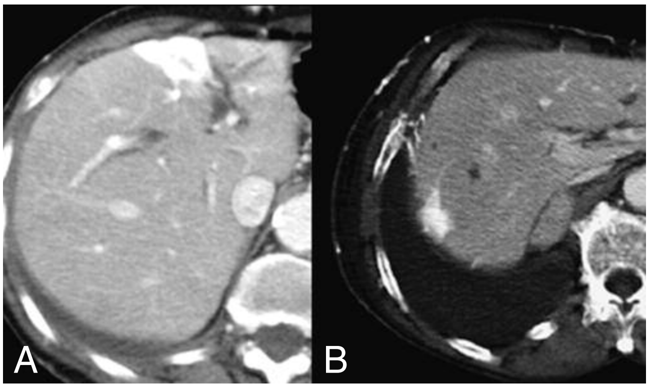

Fig. 17. — Two different patients with superior vena cava syndrome. A: There is an area, localized at segment IV, of intense and early enhancement, mimicking a hypervascular focal lesion. B: This case shows subcapsular venous collateral vessels at the right liver lobe again leading to a hyperdense pseudo-tumoral focal lesion.

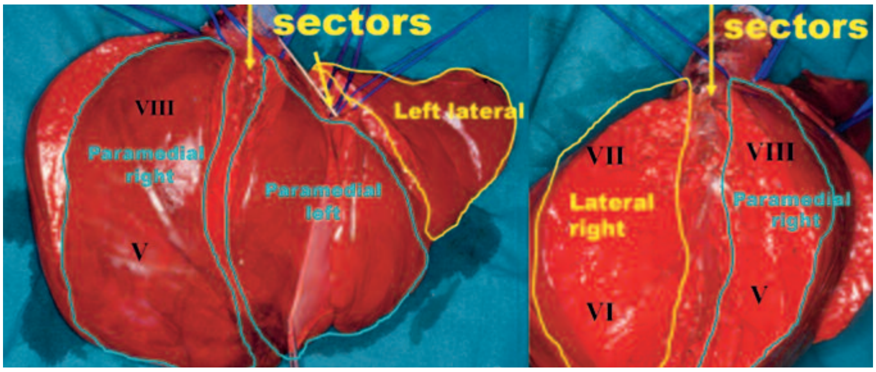

Fig. 18. — The liver can be divided into four sectors: left lateral, paramedial left, paramedial right and lateral right. The separation lines (arrows) between sectors are called portal fissures and contain the hepatic veins.

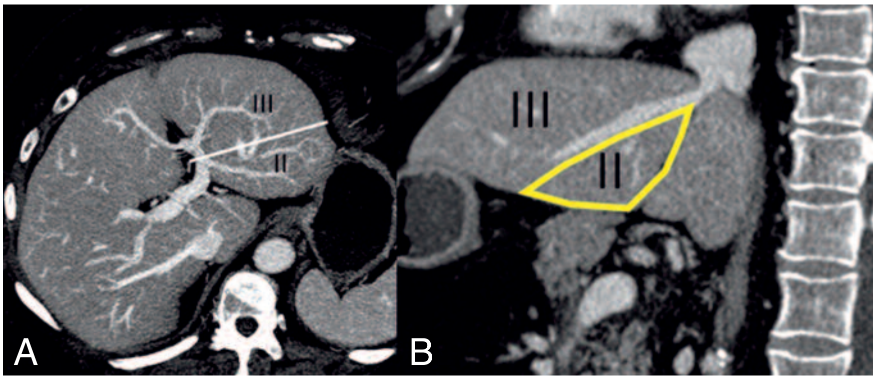

Fig. 19. — The problem of separation between segment II and III on CT. A: On the axial plane we trace a line that intersects both the middle portion of umbical segment of portal vein and the left hepatic vein. Posterior to that line is segment II and anterior is segment III. B: On the sagittal plane the distinction between segment II and III is straightforward. Posterior to the left hepatic vein is segment II and anterior is segment III.

recently by Couinaud (38), and Bismuth (39).

Couinaud (1957) proposed a liver segmentation system based on portal and hepatic veins. It includes eight segments divided by the second order branches of portal vein with the argument that functional segmentation using the veins is preferred over arteriobiliary segmentation since portal vein branches off first, with arteriobiliary following the vein distribution. Portal segmentation is also simpler to use because it is less prone to anatomical variations.

Couinaud divided the liver into two functional parts: the left and right liver, separated by a main portal fissure containing the middle hepatic vein, known as Cantlie's line. Surface markings of this line are inaccurate but grossly correspond to a plane joining the gallbladder fossa anteriorly to the left side of the inferior vena cava posteriorly. The left and right hemilivers are further subdivided by the left and right hepatic veins, lying in the left and right portal fissure, corresponding to the bed of the hepatic veins (Fig. 18).

The right hemiliver is subdivided into two main sectors drawing a second line that vertically runs along the right portal vein bifurcation: a right lateral sector, lying posterolaterally and a right paramedian sector lying anteromedially. Each sector is formed by two segments: the right lateral sector by segments VI and VII and right paramedian sector by segments V and VIII.

The left portal fissure lies in the middle of left anatomical lobe and corresponds to a plane passing from the confluence of the left hepatic vein with the inferior vena cava towards the most lateral left lobe tip, dividing it into a left paramedian and lateral sectors. The left paramedian sector consists of segments III and IV. The left lateral sector is comprised only of segment II, which is the posterior part of the left lobe (Fig. 19). Sectional imaging is not well suited to determine the exact boundary between segments II and III. Its division can be assumed from a line drawn from the middle portion of vertical part of the left portal vein that joins the left hepatic vein. Oblique reconstructions using MIP algorithms can provide additional help for its demonstration (Fig. 19).

From a functional point of view, the caudate lobe (or segment I) is an autonomous segment since its vascularization is independent from the main portal division and main hepatic veins.

Bismuth has brought together the Couinaud's cadaveric system in situ (38) and the classification system of Goldsmith and Woodburn in vivo (37). He distinguished three planes (scissurae), hosting the hepatic veins and a transverse plane passing through the right and left portal branches. The three hepatic veins divided the liver into four sectors. each supplied by its own portal pedicle (containing an arterial, portal vein, and bile duct branches).

Although the above outlined concepts may be correct in some patients, from a morphologic point of view they can be questionable (40, 41). Anatomists such as Platzer and Maurer (40) pointed out that the variability of segmental boundaries is too large to render any scheme viable. Fasel et al (42) confirmed that the vertical planes that intersect the trunks of the hepatic veins do not correspond to the presumed intersegmental boundaries. Radiologists, as well, have published observations questioning the radiologic methods currently used for delineation of the segmental anatomy of the liver. Nelson et al (43) and Soyer et al (44) concluded that indirect landmarks are not reliable for the correct delineation of portal venous segments and subsegments. In opposition to the traditional landmarks (using the planes of the three major hepatic veins and the portal trunks as segmental boundaries), radiologists can localize lesions attributing them to the nearest peripheral portal vein branches. Rieker et al. (45) showed differences in segmental locations in 16% of the lesions analysed. These different locations were due to the path of the portal trunks or of the peripheral portal branches crossing the planes of the major hepatic veins. With current radiologic procedures based on indirect landmarks it is therefore not possible to exactly determine segmental and subsegmental anatomy of the liver. Also, every concept of flat planes delineating portal venous territories is an oversimplification which is not in full agreement with anatomic reality.

True segmental and subsegmental determination is possible only with methods that account for the actual anatomy of the portal venous tree, incorporating off-branching of third and fourth-order portal branches. This can be more readily appreciated when reading the 3D axial dataset in interactive cine mode display.

Conclusion

Radiologists must be knowledgeable on liver vascular anatomy, its variants and the vascular landmarks allowing functional liver segmentation. . Angio-MDCT of the liver is often the standalone technique in the preoperative evaluation of patients for a variety of different clinical scenarios. Routine use of advanced post-processing algorithms and segmentation techniques such as maximum intensity projections and three-dimensional volume renderings provide high quality graphic display which assists in the demonstration and understanding of its variable liver blood supply. "Non-portal" venous supply to the liver can mimic focal liver pathology and the exact location of the parenchymal abnormalities anticipates interpretative pitfalls. Although a single, worldwide-accepted classification of the liver anatomy does not exist, radiologists should favor the use of the terminology provided by the segmentation-based functional anatomy of the liver.

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