INTRODUCTION
From the first liver resection by A. Luis in 18861 to modern day liver transplantation, hepatobiliary surgery has witnessed major advancements over the last century. Much of this technical achievement has been attained on the back of progressively improved understanding of the liver anatomy and its potential variants. From Cantlie to Couinaud, many anatomists contributed towards this modern-day understanding of the liver anatomy. The liver, by virtue of its friability and propensity to bleed from rich vascularization, continues to be a surgical challenge for today's surgeon despite access to modern instruments and equipment. Good working knowledge of the hepatic anatomy with its variants is therefore an important prerequisite to successful hepatobiliary surgery and the only way to minimize associated complications.

This chapter reviews the anatomy of the liver in some detail. All functional components of the liver, including arterial supply, venous outflow, biliary tree and lymphatics, are sequentially reviewed.

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FUNCTIONAL SURGICAL ANATOMY

The functional anatomy of the liver has been a subject of much debate and research over the last century and even till today among surgical scholars. The internal liver structure has been clarified.2–4,5–8 This “functional anatomy” describes liver architecture in terms of hepatic segments based on the distribution of portal pedicle and location of hepatic veins. Essentially, the three main hepatic veins divide the liver into four sectors, each of which receives a portal pedicle with an alternating arrangement of hepatic vein and portal pedicle.

According to Couinaud’s landmark description,7 the liver parenchyma overlying the hepatic veins is termed a scissura. Thus, the main portal scissura (better known as Cantlie’s line) contains the middle hepatic vein and extends from the middle of the gallbladder anteriorly to the left of the vena cava posteriorly. This imaginary line divides the liver into right and left lobes and has been used by surgeons to delineate the lobes as such. Of clinical significance, the left and right lobes of the liver are independent in terms of portal and arterial vascularization and of biliary drainage. This anatomical divide is important in determining types and extent of resections.

Subsequently, the right and left lobes are further subdivided into two sectors each by two other portal scissurae. The right portal scissura divides the right lobe into anteromedial and posterolateral sectors. The right hepatic vein runs in the right scissura. Each of these sectors is further subdivided into segments. The anteromedial sector contains segment V anteriorly and segment VIII posteriorly. The posterolateral sector contains segment VI anteriorly and segment VII posteriorly. The left portal scissura containing the left hepatic vein divides the left lobe into anterior and posterior sectors. Of note, the left portal scissura is not within the umbilical fissure but located posterior to the ligamentum teres. The umbilical fissure overlies a portal pedicle and thus divides the anterior sector into segment III and IV (quadrate lobe). The posterior sector is only composed of segment II.

The caudate lobe is referred to as segment I. It lies posteriorly in close proximity to the inferior vena cava and segment IV. Functionally, it is an autonomous segment as it receives its blood supply from both the right and left branches of the hepatic artery and portal vein. Also, its venous drainage is directly into the inferior vena cava instead of the hepatic vein. This is important in setting of Budd-Chiari syndrome. Obstructed hepatic veins cause hepatic outflow to be directed through a hypertrophied caudate lobe into the inferior vena cava.
Liver Anatomy and Anatomic Variants

CLINICAL SIGNIFICANCE

Knowledge of the functional anatomy is important to undertake various types of partial hepatectomies such as lobectomy, and segmentectomies. Understanding the anatomy is less important when planning wedge or “nonanatomic” liver resections. Good working knowledge of the vasculature and bile ducts allows accurate resection with a lower chance of biliary complications, including leaks. Knowledge of the anatomy can also ensure...
that the post-resected liver remains viable with normal arterial inflow and venous outflow to allow prompt regeneration.

**LIVER BLOOD SUPPLY**

The liver normally receives 25% of the total cardiac output and is unique in that it receives its blood supply from two main sources: the hepatic artery and portal vein. The hepatic artery provides about 25% of the hepatic blood flow and 50% of the oxygen supply. The portal vein contributes about 75% of the blood flow and 50% of oxygen supply. Mixing of the arterial portal blood occurs in the sinusoids which are drained by the hepatic veins into the inferior vena cava (IVC).

**HEPATIC ARTERY**

The anatomy of the hepatic artery and its variants has been described in the literature. Aberrant hepatic arteries are found in 45% of population, based on postmortem examinations. An aberrant artery is *accessory* if it supplies a segment of the liver that also receives blood supply from a normal hepatic artery. It is a *replacing* artery if it is the only blood supply to such lobe or segment.

The common hepatic artery originates from the celiac trunk in 86% of the population. Other sources are superior mesenteric artery (2.9%), aorta (1.1%) and, very rarely, left gastric artery. After its origin, the common hepatic artery runs horizontally along the upper border of the head of the pancreas and gives off the gastroduodenal (GDA) artery posterior and superior to the duodenum. The supraduodenal artery and right gastric artery originate just distal to the GDA. The continuation of the hepatic artery beyond the origins of these vessels is known as the hepatic artery proper (HAP). It turns upwards to ascend in the lesser omentum, enveloped by the hepatoduodenal ligament, in front of the epiploic foramen of Winslow. Within the hepatoduodenal ligament, the HAP lies to the left of the common bile duct and anterior to the portal vein. Together, the hepatic artery proper, the common bile duct and the portal vein form the *portal triad*. Within the ligament, the hepatic artery proper divides into right and left hepatic arteries.
The right hepatic artery is a branch of the hepatic artery proper in the majority of the population; however, in 17% of subjects, it arises from the superior mesenteric artery. A “replaced” right hepatic artery is more common than an “accessory” right hepatic artery. Inadvertent ligation of a replaced right hepatic artery, especially where it crosses the junction of the cystic duct and common bile duct, during cholecystectomy, deprives blood supply to the right lobe of the liver and can lead to significant complications. In contrast, ligation of an accessory right hepatic artery that derives from superior mesenteric artery has less significant consequences. At the porta hepatis, the right hepatic artery normally passes to the right behind the hepatic duct and anterior to the portal vein to enter the Calot triangle formed by the cystic duct, the hepatic duct and the liver. In 15% of individuals, however, it may pass anterior to the hepatic duct. This variation is worth remembering during exploration of the common bile duct or routine cholecystectomies.

Figure 2. (A) Normal hepatic artery from celiac trunk. (B) Accessory left hepatic artery from left gastric artery. (C) Replacing common hepatic artery arising from superior mesenteric artery. (D) Replacing right hepatic artery arising from superior mesenteric artery. Hepatic Surgical Anatomy. Surg Clin N Am 84 (2004) 413–415; used with permission.
Before entering the liver, the right hepatic artery gives off the cystic artery. Within the liver, the right hepatic artery divides into anterior and posterior segmental arteries which divide further into superior and inferior arteries to supply the respective subsegments. An artery for the caudate lobe also originates and supplies the caudate process and the right side of the caudate lobe. These arteries are found under the respective bile duct branches.

The left hepatic artery usually originates from the HAP. An aberrant left hepatic artery originating from the left gastric artery occurs in 30% of patients. In this variant form, the left hepatic artery is a replaced versus accessory artery in a ratio of 1:1. If replaced, only the right hepatic artery comes off from the celiac axis, whereas, in the presence of an accessory vessel, the common hepatic artery takes its usual course and supplies a right and a left hepatic artery. Ligation of a replaced left hepatic artery, such as during gastrectomy or laparoscopic Nissen fundoplication, would compromise the blood supply to the left lobe of liver. In addition, an accessory left hepatic artery may also come from the right hepatic artery.

Figure 3. Variations in branching of left hepatic artery. (A) Bifurcation into medial and lateral segmental arteries. (B) Division of lateral segmental artery into laterosuperior and lateroinferior branches. (C) The left medial segmental artery arises from right hepatic artery. Hepatic Surgical Anatomy. Surg Clin N Am 84 (2004) 413–415; used with permission.
After its origin, the left hepatic artery supplies the entire left lobe of liver in 40% of patients by dividing into medial and lateral segmental arteries. Interestingly, in 25% of patients, the left hepatic artery supplies only the left lateral segmental; the left medial segment being supplied by a branch of the right hepatic artery crossing the midline. The left hepatic artery also gives off a branch for the caudate lobe supplying its left side.

**PORTAL VEIN**

The portal vein forms behind the head of the pancreas at the level of L2 through a confluence of the superior mesenteric and splenic veins. It runs behind the first portion of the duodenum and then along the right border of the lesser omentum — as part of portal triad — for a length of 8–10 cm. In its upward course, the portal vein receives the *coronary vein*, which is a continuation the left gastric vein and the esophageal venous plexus. At the liver hilum, it divides into right and left branches to the respective lobes.

The right branch of the portal vein is shorter of the two branches and is located anterior to the caudate process. Near its origin, it gives off a branch for the caudate lobe and then divides into anterior and posterior segmental branches, which further subdivide into superior and inferior subsegmental branches for respective parenchymal subsegments.

The left portal vein is smaller and longer than its counterpart. It also gives off a caudate lobe branch at its origin following which it divides into medial and lateral branches. The medial vessel contains a dilatation, the *pars umbilicus*, which represents the orifice of the obliterated embryonic ductus venosus.

**Portal Vein Variations and Anomalies**

Historically, shunt procedures for portal hypertension have created considerable interest in the anatomy of the portal vein. Of note, however, the portal vein system has fewer anatomic variants than the hepatic arterial system. The usual anatomic description of the formation of portal vein is found in 50% of patients. In the other half, the inferior mesenteric vein enters the junction of the splenic and superior mesenteric veins, or it joins the superior mesenteric vein. Rarely, the portal vein may lie anterior to the head of the pancreas and duodenum.
Section 1: Liver Disease

Relationship Between Hepatic Artery and Portal Vein Blood Flow

Hepatic arterial blood flow is unique in that it is not determined by the oxygen demand of liver parenchymal cells. Instead, portal blood flow is the major intrinsic regulator of hepatic arterial tone. The hepatic arterial buffer response\textsuperscript{16} causes changes in hepatic arterial blood flow in response to any portal inflow alterations thus tending to regulate total hepatic blood flow at a constant level. This mechanism depends on portal blood flow removing local concentrations of adenosine. With decreased portal vein inflow, less adenosine is washed out, causing its concentration to rise, thereby resulting in arterial dilatation and increased arterial blood flow.

HEPATIC VEINS

Outflow of the liver is facilitated by the hepatic veins. Three main hepatic veins and many smaller veins drain blood from the liver into IVC. As

Figure 4. Portal vein lying anterior to pancreas. Used with permission from Netter’s gastroenterology. Martin H Floch.
mentioned previously, the hepatic veins are found intraparenchymally and form the bases for sectors and segments of the liver.

The right hepatic vein is the largest of the three veins. It lies in the right scissura and drains both posterior segments and anterosuperior segment. Together, this constitutes segments V, VI, VII and part of VIII.

The middle hepatic vein serves the left lobe of the liver together with the left hepatic vein. It lies in the median scissura and drains segments IV, V, and part of VIII.

The left hepatic vein lies in the upper portion of the left scissura and drains the segments II, III and part of segment IV. In 60% of cases, the left and middle veins unite to enter the IVC as a single vein. This anatomical confluence is often used for implantation in the caval preservation of technique during the liver transplant. Formal clamping of the vena cava can be avoided by creating a common orifice of the middle and left hepatic veins and clamping the confluens using that common orifice for the upper caval anastomoses of the allograft.

ANATOMY OF BILIARY TREE

The next anatomic system to be discussed in liver anatomy is the biliary system. In order to prevent biliary complications after liver surgery, anatomical knowledge of biliary ductal system is of vital importance.

The bile ducts commence by small passages in hepatocytes which communicate with canaliculi termed *intercellular biliary passages*. Bile flows from canaliculi through ductules into interlobular bile ducts found in portal pedicles. In segmental and subsegmental pedicles surrounded by a Glissonian sheath, bile ducts are found alongside the hepatic artery and portal vein. The segmental bile ducts join to form the right and left hepatic ducts which come together to form the common hepatic duct. As mentioned previously, the common hepatic duct runs along the hepatic artery and portal vein which together form the portal triad.

The right hepatic duct is formed by the union of the anterior and posterior branches at porta hepatis. Each branch is further bifurcated into superior and inferior branches to drain the four segments of the right lobe. These include segments V, VI, VII, VIII. This pattern is usually present in 72% of patients. In the remainder, the anterior, or sometimes posterior, branches empty into the left hepatic duct. The left hepatic duct is formed by the medial and lateral branches converging together. Each branch is formed by superior and inferior branches of the respective segments.
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Overall, the left hepatic duct drains segment II, III and IV of the liver. Again, this arrangement is present in 67% of patients.

The caudate lobe (segment I) is unique in that its biliary drainage enters both the right and left hepatic duct systems in 80% of the population. In 15% of patients, it drains only in the left hepatic duct and in the remaining 5% of cases drains only into the right hepatic system.

Gallbladder and Cystic Duct

The gallbladder is a reservoir of bile located on the undersurface of the right lobe of the liver within the cystic fossa and separated from the hepatic parenchyma by the cystic plate. Sometimes it may be deeply embedded in the liver.

Anomalies of the gallbladder are numerous. These include bilobar gallbladders with a single cystic duct but two fundi, duplication of the gallbladder with two cystic ducts, double cystic duct draining unilocular gallbladder. Congenital diverticulum of the gallbladder with a muscular layer has also been described. The cystic duct arises from the infundibulum.
Figure 6. Main variations in gallbladder and cystic duct anatomy: (A) duplicated gallbladder, (B) septum of the gallbladder, (C) diverticulum of the gallbladder, (D) variations in cystic ductal anatomy, (E) Different types of union of the cystic duct and common hepatic duct: (a) angular union, (b) parallel union, (c) spiral union. Used with permission from Surgery of the liver, biliary tract and pancreas. (4th Edition) Volume 1. LH Blumgart.
Section 1: Liver Disease

of the gallbladder and joins the common hepatic duct at an angle to form the common bile duct. The cystic duct usually measures 2–4 cm in length and contains prominent concentric folds known as the spiral valves of Heister. The cystic duct frequently exhibits a tortuous or serpentine course. The normal diameter of the cystic duct is variable, ranging from 1–5 mm.

Congenital anatomic variants of the cystic duct are common occurring in 18%–23% of patients. The cystic duct inserts into the middle one-third of the extrahepatic bile duct in 75% of cases and into the distal one-third in 10%. It most commonly inserts from a right lateral position but may have an anterior or posterior spiral insertion, low lateral insertion with a common sheath enclosing the cystic duct and common bile duct, proximal insertion, or low medial insertion at or near the ampulla of Vater.

The level of cystic duct insertion may vary, with an abnormal proximal or distal union accounting for 55% of biliary ductal anatomic variants. The cystic duct may join the right hepatic duct, the left hepatic duct (rarely), or the common hepatic duct high in the porta hepatis. It empties into the proximal common hepatic duct or into the right hepatic duct in 0.3% of cases. The insertion may be low in the intrapancreatic or intraduodenal portion or at the level of the ampulla of Vater. Rarely, the cystic duct inserts directly into the duodenum.

A cystic duct that parallels the common hepatic duct is found in 20% of patients. This anatomy may be problematic at cholecystectomy. Ligation of the cystic duct too close to the common hepatic duct may result in stricture of the latter. Similarly, mistaking the cystic duct for the bile duct can result in iatrogenic injury such as inadvertent ligation or transection of the extrahepatic bile duct.

LIVER HISTOLOGY

The structural and functional organization of the liver has been described by hepatic lobule and hepatic acinus models respectively. The lobule model describes the liver as being organized into lobules which take the shape of irregular polygonal prisms. At the corners between adjacent lobules is the portal triad containing the hepatic artery, portal vein and bile duct. Along the central axis of each lobule runs a central vein which is a branch of the hepatic vein. Occupying the bulk of lobules are hepatocytes arranged into cords separated by sinusoids. The sinusoids are
structurally different in that they are lined by fenestrated endothelium which has no underlying basement membrane. Therefore, fenestrations allow blood plasma to flow easily over the exposed surface of hepatocytes in the space of Disse (space between endothelium and hepatic cords). Bile canaliculi formed by apical surfaces of adjacent hepatocytes form a tiny network of passages contained within each cord.

Blood enters the sinusoids from the terminal portal venules. End arterioles of the hepatic arteries also drain into terminal portal venules allowing mixing of the blood. The large sinusoidal volume permits this blood to associate intimately with the hepatocytes, allowing transfer of substances across the hepatocyte membranes. Kupffer cells are associated with the sinusoids allowing destruction of bacteria.

The liver acinus encompasses the liver tissue that is served by a single terminal branch of the hepatic artery. These small vessels extend out from portal areas, along the boundaries between adjacent lobules. An acinus is typically diamond-shaped in cross section, with a hepatic arteriole crossing the center and with central veins at the two opposite corners. The acinus includes triangular portions of two adjacent lobules.
LYMPHATICS OF THE LIVER

The lymphatic system of the liver is divided into superficial and deep systems and has a different organization from the vasobiliary system. It is important to know the anatomy of the lymphatic system when assessing the spread of malignancies to locoregional lymph nodes.

The superficial system drains in four directions:

1. Vessels that drain the coronary and right triangular ligaments enter the thoracic duct.
2. Vessels of the porta hepatis, close to the falciform ligament, enter the hepatic nodes from which they gain access to celiac nodes and then to the intestinal trunk.
3. Vessels in the posterior part of the left lobe pass through the esophageal opening to enter the pericardia lymph nodes.
4. Vessels which drain the rest of the right lobe enter the celiac nodes.
The deep system is the system with greater lymphatic flow. It forms ascending and descending trunks. The ascending trunk ends in nodes close to IVC in the mediastinum. The descending trunk leaves the porta hepatis and enters the hepatic nodes.

All the vessels (except the paracardial and the ascending trunk, which end in the nodes of the inferior vena cava) enter into the celiac node. From these nodes, they pass into the intestinal lymph trunks, which then enter the cisterna chyli or the abdominal confluence of lymph trunks. The cisterna chyli drains into the thoracic duct. The exceptions enter the bronchomediastinal trunk to reach the right jugulosubclavian junction or the right lymph duct.

CONCLUSION

The rapid evolution of hepatobiliary surgery with performance of radical operations such as trisegmentectomies and split liver transplantation makes knowledge of hepatic anatomy even more imperative for today’s surgeon compared to any other era. A clear understanding of the relationships between major anatomic structures in the liver allows surgeons the ability to mitigate risk of surgery and ensure their patients receive the highest quality of care.

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