Anatomy of the liver: An outline with three levels of complexity –
A further step towards tailored territorial liver resections

Pietro Majno1,⇑, Gilles Mentha1, Christian Tosö1, Philippe Morel1, Heinz O. Peitgen2, Jean H.D. Fasel3

1Hepatobiliary Center, Digestive Surgery and Transplantation Units, Department of Surgery, University Hospitals of Geneva, Switzerland; 2Fraunhofer Institute for Medical Image Computing, Bremen, Germany; 3Anatomy Sector, Department of Cellular Physiology and Metabolism, Faculty of Medicine, University of Geneva, Switzerland

Summary

The vascular anatomy of the liver can be described at three different levels of complexity according to the use that the description has to serve. The first – conventional – level corresponds to the traditional 8-segments scheme of Couinaud and serves as a common language between clinicians from different specialties to describe the location of focal hepatic lesions. The second – surgical – level, to be applied to anatomical liver resections and transplantations, takes into account the real branching of the major portal pedicles and of the hepatic veins. Radiological and surgical techniques exist nowadays to make full use of this anatomy, but this requires accepting that the Couinaud scheme is a simplification, and looking at the vascular architecture with an unprejudiced eye. The third – academic – level of complexity concerns the anatomist, and the need to offer a systematization that resolves the apparent contradictions between anatomical literature, radiological imaging, and surgical practice. Based on the real number of second-order portal branches that, although variable averages 20, we submit a system called the “1-2-20 concept”, and suggest that it fits best the number of actual – as opposed to idealized – anatomical liver segments.

Introduction

Despite the remarkable advances in the understanding of the liver in health and disease, the anatomy of this organ still remains controversial. The lack of a common language on liver anatomy makes communication difficult, especially when reporting surgical procedures such as liver resections [1–3], and the lack of a coherent conceptual representation is unsatisfactory for the anatomist. The aims of this short overview, dividing liver anatomy in three levels of increasing complexity adapted to the use that the description has to serve, are: (1) to briefly recall the basics of Couinaud’s conventional representation, (2) to summarise the arguments and the tools for respecting the real, as opposed to the theoretical, vascular anatomy in liver resections, and (3) to present a systematic model for the number and distribution of liver vascular territories that appears to reconcile unprejudiced observation to the seemingly contradictory descriptions of the literature.

1st – conventional – level: Vascular anatomy as a common clinical language

An idealised scheme with eight liver segments

The merit of recognizing a relatively simple pattern of the vascular anatomy of the liver has to be credited to the French surgeon Claude Couinaud [4]. A summary of this work was popularised by two landmark articles by Henri Bismuth [5,6] commonly regarded as the beginning of the era of liver surgery according to anatomical principles.

The scheme is based on the concept that the main portal vein divides into a right and a left branch, defining a right liver and a left liver, and that the three efferent hepatic veins (left, middle, and right) interdigitate with the two portal branches as the fingers of two opposite hands. The separation between the right and the left liver is evident when the right and left branch of the portal vein are injected with resins of different colours (Fig. 1A). The plane of separation can be approximated as a plane going from the gallbladder bed to the inferior vena cava, and in this plane runs the middle hepatic vein, which can be taken as the watershed between the right and the left liver.

According to the common representation of Couinaud’s scheme (Fig. 1B), a relatively constant pattern of branching of the portal vein then occurs within both the right and the left liver. On the right, the right portal branch divides into two second-order sectorial branches, defining a right anterior sector...
and a right posterior sector, separated by the plane in which runs the right hepatic vein. The third-order divisions of the sectorial branches will separate each sector of the right liver into two segments (5/8 and 6/7, respectively). In practice, it is convened that all these separations (sectorial and segmental) in the right liver occur at the level of the portal bifurcation. In the left liver, the left portal branch describes an arch towards the round ligament. The concavity of this arch embraces segment 4 (divided into a cranial 4a and a caudal 4b subsegment), and the convexity gives off two branches, a first one for segment 2 and a more distal one for segment 3, separated by the left hepatic vein. The third-order branch of the liver into eight branches, commonly attributed to Claude Couinaud and popularised by Henri Bismuth (Courtesy of Denis Castaing, Centre Hepatobiliaire, Hôpital Paul Brouse, Villejuif, France). The first-order right portal branch divides into two second-order branches for anterior sector (dividing into two third-order branches for segments 5 and 8) and a posterior sector branch (segments 6 and 7). The insert reproduces a map of the districts (arrondissements) of Paris, allegedly having inspired Claude Couinaud for the naming of the segments of the liver at a time when the common anatomical representations were pictured as antero-posterior views (Henri Bismuth, personal communication, 1996). (C) Couinaud's segmentation as applied to CT imaging; IVC, inferior vena cava; lhv, left hepatic vein; LPV, left portal vein; mhv, middle hepatic vein; PB, portal bifurcation; PT, portal trunk; raspv, right anterior sectorial portal vein; rhv, right hepatic vein; rpspv, right posterior sectorial portal vein; 1–8, segments' numbering system according to Couinaud. (Courtesy of Pierre Lubeyre, Department of Radiology, University Hospitals of Geneva, Switzerland).
Review

originating from the portal bifurcation, and its parenchyma is drained by a variable number of separate hepatic veins directly into the vena cava.

Couinaud named the eight segments of the liver from the centre (segment 1) clockwise when a cast of the liver vessels is seen from above (as was the case in pre-CT radiology), allegedly reproducing the distribution of the districts (arrondissements, in French) of Paris. On modern axial imaging, where the patient is seen from below, the superior segments appear on slices above the portal bifurcation and the inferior segments on slices below it (Fig. 1C).

Examining the intact liver surface from the outside, the position of the segments can only be approximated, and the boundaries between the segments cannot be defined, with the partial exceptions of segments 3 and 4 (the round ligament), of segments 4 and 5 (the gallbladder fossa) and of the left part of segment 1, corresponding to the Spigel’s portion of the caudate lobe. In the views offered by modern axial imaging, however, the vascular landmarks (the three hepatic veins and the portal bifurcation) of Couinaud’s scheme are clear, and the location of a focal lesion can be described on a frame of reference that is commonly agreed among all specialties involved. Indeed, reference charts based on Couinaud’s anatomy are particularly useful to summarise the records of patients with multiple lesions that need to be identified and followed in time, and can be downloaded from the internet [7]. The reader will notice, however, that despite Couinaud’s description of segments as elementary anatomical units corresponds to the portal branches, the commonly used working system is in fact based on the three hepatic veins (Fig. 1). In this simplified conventional language, the bifurcation between the right and the left main branch is the only element of the portal vein that must be identified, to define the superior segments (8 and 7) and the inferior segments (5 and 6).

2nd – surgical – level: Vascular anatomy for the liver surgeon

Beyond the eight-segments scheme, towards tailored territorial liver resections

Modern liver surgery and transplantation have reached a level of complexity, in which the traditional 8-segments scheme is insufficient [8–12]. The reasons why the actual (rather than the ideal) vascular anatomy has to be respected are manifold:

(1) In liver resections in general, (i.e., for all kinds of indications), removal of devascularised parenchyma, and especially of parenchyma deprived of its biliary drainage ( bile ducts are an intrinsic part of the portal pedicles), helps avoiding postoperative infections and biliary leaks.

(2) In liver resections for hepatocellular carcinoma (HCC):

(a) The majority of resections for HCC are performed on livers with cirrhosis or fibrosis that diminishes the hepatic functional reserve and increases the risks of hepatocellular failure. Resections have therefore to be as conservative as possible in the sacrifice of non-tumoural liver [8,13,14].

(b) Intrahepatic metastases of HCC tend to develop in the territory of the portal vein feeding the tumour, and in particular for larger tumours, the corresponding portal territories have to be removed as appropriate [13–15].

(3) In liver resection for colorectal metastases, surgery has to be conservative of healthy liver tissue because:

(a) Chemotherapy associated liver changes impair the functional hepatic reserve [16].

(b) Patients often need two-stage or repeat surgery, as a planned curative strategy to eradicate advanced disease, or for recurrences after a first resection [17–20].

(4) In liver transplantation, segmental procedures are required:

(a) For paediatric transplantations in cases of very small babies where only one segment can be accommodated in the recipient [19].

(b) For living-donor transplantations where anatomical variations do not allow to take simply the right or the left liver [8].

During liver resections, three technical approaches allow recognising the portal territories more precisely than it is possible from extrapolation of the ideal planes used to define the traditional Couinaud’s segments (i.e., to move from the conventional into the surgical level of complexity).

The first technical approach is the extra-hepatic dissection of the portal and arterial branches within the liver hilum, and selective ligation or clamping, to see a line of ischemic demarcation. Dissection of vessels within the hepatic hilum is used when the plane between the right and the left liver has to be seen, or to define the boundaries of putative sectors, but it cannot be used to resolve smaller territories of the right liver, as in the right liver the dissection of the structures within the Glissonean pedicles (intra-Glissonean plane) cannot be pursued beyond the hepatic hilum (on the left, by converse, the intra-Glissonean plane can be followed up to the round ligament).

The second and third technical approaches can be used to resolve smaller anatomical units, and will be detailed briefly (the interested reader is encouraged to refer to the original articles and their bibliography). The second approach is based on ultrasound identification of a portal branch and its occlusion (together with occlusion of a main hepatic artery): with a balloon followed by indigo carmine blue injection as described originally by Makuuchi et al. as early as 1985 [13], by tattooing and primary surgical ligation [13,21], or by ultrasound-guided finger compression [22]. The same approach can be used in mono-segmental transplantations [23]. The vascular injection/occlusion techniques require remarkable skill and practice, but they appear successful and reproducible in centres where local anatomical resections of small HCCs are customary [12].

The third approach is especially suited for lesions situated in the inferior part of the liver, or for larger liver resections exposing the hilar plate (the condensed Glissonean sheath of the upper hepatic pedicle, containing the bifurcation of the main hepatic ducts) on the parenchymal side. The technique consists of following the branching of the pedicles as if they were branches of a tree whose bark is the Glissonean sheath, and to prune the branches feeding the territory that has to be removed. This technique, the intrahepatic or “Glissonean” (“extra-Glissonean”, more precisely) approach originally applied by Takasaki [24] is relatively bloodless because the surgical plane immediately in
contact to the Glissonean sheaths avoids entering major hepatic veins, and minor branches are easily controlled by cautery or spontaneous haemostasis in the low venous pressure environment allowed by modern anaesthesia.

With the third (intrahepatic, extra-Glissonean) approach, even small territorial pedicles can be identified and resected or preserved as the case dictates, regardless whether they conform with the traditional segmental representation, leaving a resection bed that has spared the portal afferents and the biliary drainage of the liver remaining in place. This is particularly evident in the conventional anterior sector (S5 and S8), for instance, where detailed anatomical studies [25], show to the trained eye a variety of ways to customize liver resections well beyond the traditional segmental scheme, yet respecting the principles of segmental surgery summarized above (Supplementary Figs. 4–9).

It is clear for the surgeon following the Glissonean approaches – or even an intra-Glissonean approach on the left (such as the round ligament approach that gives access to left portal vein in split liver procedures [26]) – that there are more 2nd order (conventionally sectorial) and 3rd order (segmental) branches than the 8-segments scheme allows for. Similarly, when leading hepatic surgeons draw illustrations of real surgical anatomy [10,27], they implicitly admit that the 8-segment scheme is an oversimplification that modern surgery has to overcome (Fig. 2B A). What is even more perplexing is that segments of the conventional Couinaud’s scheme are often fed by 3rd-order (therefore segmental) branches originating from different 2nd-order branches, or sometimes by 3rd- and 4th-order branches (Fig. 2A).

Modern radiology has made major contributions in visualizing the portal pedicles and the hepatic veins, and surgeons can identify preoperatively the real vascular anatomy more precisely than ever before (Fig. 2B and C). More complex computerized programs that semi-automatically calculate the vascular territories corresponding to each vessel identified on a radiological investigation are available, and they allow computing precisely the number and the volumes of vascular territories (Fig. 3A) [12,28]. In almost every case, however, it can be noted that a tributary is still paid to the 8-segment scheme: reconstructions are presented with different vessels contributing to one traditional segment (Fig. 3A).

From a fresh reading of the best surgical literature, and from everyday practice with modern radiology and surgery, it is obvious that there are more branches and more variability than the conventional 8-segment scheme suggests. We have been particularly impressed by the detail, in which the anatomy can be resolved and transferred to the operating theatre when the surgeons themselves are empowered with the newer radiological tools (Fig. 2B and C, and supplementary Figs. 5–8). This more refined anatomy will need a change in the language used in scientific papers, still debated [1,29,30] and equivocal. It seems premature at this stage, however, to fix on new proposals, and we share the view that beside the most common and clear terms of right hepatectomy (or, less preferably, right hemi-hepatectomy), corresponding to the resection of the first-order territory of the right portal vein, the enumeration of the conventional segments should suffice at present, accommodating the most relevant variations into descriptive terms (e.g., ventral or dorsal branch S8 [3]; or naming territorial branches with numerals after the figure of the conventional segment, such as is done in the case illustrated in the Supplementary Figs. 5–8).

3rd – academic – level: Vascular anatomy for the anatomist

A further call for an unprejudiced view on the intrahepatic vessels

In spite of the remarkable advances in radiological imaging and surgical techniques, looking at the detailed branching patterns of the complete intrahepatic vascular tree, and systematizing them into a framework that reconciles the findings of compared, developmental and descriptive anatomy, remains the anatomist’s privilege. It could be argued that the vascular anatomy of the liver has been studied extensively for centuries, and nothing new or useful can be added. This view must be reconsidered. Indeed, in the last decade or so, a raising number of observations call Couinaud’s conventional scheme into question, either explicitly or implicitly, both in the surgical [3,10,27,30–33] and radiological context [34–36]. Recently, Hjortsjö’s anatomical model, proposing 6 sectors in the liver has regained interest, was found to be fitting usefully with radiological and surgical observations in particular concerning a partition plane in the conventional anterior sector, and underlines a very plausible symmetry between the right and the left liver [33] (Supplementary Fig. 3). Couinaud himself depicted the high variability of 2nd order and 3rd order portal branches (Supplementary Figs. 1 and 2), implicitly admitting that grouping the branches into a fixed number of segments was to be taken as a simplification, and proposed later adaptations of his system [37,38].

Because of the inconsistencies between the anatomical reality and the Couinaud scheme, we reviewed the anatomical literature and studied the portal venous branching pattern with an unprejudiced view in corrosion casts, also reconstructed with high definition CTs [39,40]. The investigations revealed that the number of 2nd order branches (including the smaller ones) given off by the left and right portal vein was always higher than the 8, on which the Couinaud’s segmental representation is based. A mean of 20 2nd order branches (range: 9–44) was counted (Supplementary Figs. 9 and 10). This finding led us to suggest a “1–2–20” concept for portal venous segmentation of the liver that can be summarized as follows: at the level of the portal trunk (which can be seen as the zero-order vessel), the liver corresponds to 1 vascular territory – the liver as a whole. At the first-generation level (in the usual case of portal vein bifurcation in the right and left portal vein branch), the same liver consists of 2 territories – the right and left hemiliver. On the next (second-order) level, the same liver has more than 8 (an average of 20) branches and therefore territories (Supplementary Fig. 10).

This high number of 2nd order branches and their corresponding territories can be grouped together according to the needs of the observer. In this way, apparently contradictory liver subdivisions occur, whereas the underlying anatomical reality remains the same (Fig. 3B 1–6). For example, the 20 or so 2nd order territories can be grouped together on the basis of the three main hepatic veins and the portal bifurcation, to obtain the usual Couinaud’s 8 segments. At this first level of complexity (the common language between radiologists, hepatologists and surgeons to situate focal lesions), the three vessels visible on the right (concave)
side of the umbilical portion of the left portal vein (Fig. 1A1) can be considered to be a single vessel in order to obtain the conventional segment 4. But at the second – surgical – level of complexity, these branches can be easily identified (indeed an artery passes between them in the corrosion cast under consideration) and must be divided separately, or can be spared as the surgical indication dictates (Fig. 3B5). And at the third – academic – level of complexity, each 2nd order branch has its own identity as and corresponds to an identifiable 2nd order parenchymal territory (Fig. 3B3).

Fig. 2. Illustrations of the 2nd level of complexity: examples of real branching of the portal system as applied in current liver surgery. (A) Schematic drawing of the Glissonean pedicles of the right anterior sector (Couinaud’s segments 5 and 8), as depicted in a recent publication from Prof Makuuchi’s unit. RtPV, right portal vein; RLS, right lateral sector; RPMS, right paramedian sector; S8 vent, ventral branch of segment 8; S8 dor, dorsal branch of segment 8; S5 vent, ventral branch of segment 5; S5 dor, dorsal branch of segment 5; MHVT-S5/8, middle hepatic vein tributary draining segments 5 and 8, respectively. Comment: the reader will notice that in this illustration segment 5 is constituted by a 3rd order branch and a 4th order branch. Reproduced with permission from [27]. (B) Anatomical-radiological study of a CT in a living donor (OsiriX® Viewer – a free open source programme), 2-D multi-planar reconstruction (2D-MPR). Several acquisitions are stacked to optimise the recognition of the vascular anatomy. (MIP – Maximum Intensity Projection – 10 slices). (C) Schematic representation of all second order left portal branches to segment 2, 3, and 4 in a living donor. The colour/pattern-coding represents the relative size of the vessels that were identified and counted. Images were acquired with a multidetector helical CT scan and viewed with stacked slices (courtesy of Dr. Steve Primmaz, University of Geneva). Comment: the reader will notice that there are more vessels to each segment than in the traditional Couinaud’s scheme, but that with this level of radiological sophistication, anatomical reality can be easily recognized and used during surgery.

Key:

- Main branch (MB) of the left portal vein according to Couinaud
- \( \frac{1}{2} \) of the MB’s diameter
- \( \frac{1}{4} \) of the MB’s diameter
- \( \frac{1}{8} \) of the MB’s diameter

<table>
<thead>
<tr>
<th>Branches’ count per segment:</th>
<th>MB</th>
<th>( \frac{1}{2} )</th>
<th>( \frac{1}{4} )</th>
<th>( \frac{1}{8} )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>S3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>S4</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>10</td>
</tr>
</tbody>
</table>
Can this freer concept of liver branches and segments be systematized and connected to other natural patterns and shapes? While such attempts can still be regarded as preliminary, analogies with fractal models of portal veins are striking (Fig. 4A) [28], and examples of trees with a distribution of branches similar to the liver are quite common to the trained eye (Fig. 4B).

The admirer of Mother Nature will not be surprised that its creations cannot be squeezed easily in a descriptive pattern,
Fig. 4. Examples of mathematical models and natural shapes with similarities to the human liver. (A) Result of the constructive optimization model for a portal vein within a predefined liver hull. Starting with a simple configuration where each liver cell is supplied by a straight vessel from the hilum, the vascular system is modified step-by-step following a mathematical minimization principle for the physical work of blood transport. (Courtesy of Professor H. O. Peitgen, Fraunhofer MEVIS, Bremen, Germany). (B) Vascular systems from corrosion cast of real human livers (B1, B2) and from the optimization process of a model within a given liver hull (B3, B4, B5). (Courtesy of Professor H. O. Peitgen, Fraunhofer MEVIS, Bremen, Germany). (C) Picture of an oak tree in the Geneva countryside. The analogies to normal liver anatomy are striking. Examples that trees can take similar shapes to the vascular architecture of the liver are not uncommon.

Fig. 3. Illustrations of the 3rd level of complexity: different representations of vascular territories are resolved in the 1-2-20 concept. (A) Vascular territories as reconstructed by computerized programs that calculate the amount of tissue corresponding to each portal (A1, A3) and hepatic venous branch (A2, A4). (Courtesy of Fraunhofer MEVIS, Bremen, Germany). Notice that in this representation, segment 5 (pink) is fed by two branches, each originating from a different order branch. (B) Taking the traditional segment 4 as an example, different subdivisions mentioned in the literature are illustrated on an individual liver – thus excluding any anatomical variation. B1, 3-D reconstruction of a CT of a liver cast; B2, Segment 4 is one territory, namely Goldsmith's and Woodburne's [41] left medial sector; B3, Segment 4 subdivided into the real number of territories as defined by the actual number of second-order branches, five in this liver (and corresponding to a meticulous description of a split procedure in which all these branches are ligated); B5, Segment 4 with four territories (a–d), corresponding to the branches as the surgeon would resect them in a territorial metasectomy; B6, Segment 4 is subdivided in a cranial and caudal portion (4a/b), according to Couinaud’s scheme. Comment: the apparently contradictory segmentations in fact are the result of different and arbitrary grouping of a given number of second order branches for “segment 4” in the one and only liver under consideration. From the surgical point of view, any of these territories can be identified and resected by one of the techniques mentioned in the text.
let alone with only 8 segments, but the effort is worth pursuing: the liver may be a further beautiful example of Nature’s endless fight between freedom and necessity.

Key Points

- The anatomy of each liver can be represented at three levels of complexity, according to the uses that the description has to serve.
- The first - conventional - level corresponds to Couinaud’s 8-segments scheme and is a very useful referential framework for the localization of focal lesions. It allows a common language between clinicians of different specialties and it is based in fact on the three hepatic veins and on the level of the portal bifurcation rather than on the portal anatomy.
- The second - surgical - level corresponds to the actual (and not the theoretical or schematic) branching of the hepatic vessels. Imaging and surgical techniques are now available to identify and follow this real anatomy during modern liver surgery, allowing anatomically tailored territorial liver resections, but this requires independence from the Couinaud representation.
- The third - academic - level is for the anatomist: a 1-2-20 concept for the number of zero-, first-, and second-order branches respectively, can take into account Couinaud’s as well as other segmentations, and does justice to the beautiful complexity of the hepatic vascular tree.

Conflict of interest

The authors declared that they do not have anything to disclose regarding funding or conflict of interest with respect to this manuscript.

Acknowledgements

The authors thank Daniel Azoulay, Henri Bismuth, Vincenzo Mazzaferrro, Osman Ratib, Laura Rubbia-Brandt, and Sylvain Terraz for the fruitful discussions and for daily work in which the ideas expressed in this article originated.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhep.2013.10.026.

References

Review


