Split Liver Transplantation

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Abstract

Split liver transplantation (SLT) creates two marginal grafts from one perfect deceased donor liver to save two recipients simultaneously. Since its inception in 1988, SLT has contributed tremendously to decreased mortality on the pediatric liver transplant waiting list. Despite unfavorable survival rates in the early experience of SLT for adults, successful outcomes have been reported by experienced centers, further substantiating the feasibility of this technique. Indeed, various advancements have encouraged more frequent use of this technique to overcome the shortage of donor livers. More than two decades of experience have documented the criteria necessary for SLT to achieve equivalent or superior outcomes to whole liver transplantation. Still, substantial challenges in surgical techniques, allocation, logistics, and ethics persist, and SLT remains underutilized worldwide. This chapter outlines the current state of SLT, focusing on donor and recipient selection, surgical techniques, outcomes, and current and future challenges such as allocation and associated ethical issues.

Keywords

Split liver transplantation • Left lateral segment • Right trisegment • Hemiliver • In situ split • Ex vivo split • Donor selection • Recipient selection • Surgical technique • Graft size • Survival • Ethical issue

Introduction

The shortage of donor livers has led transplant programs to seek innovative ways to increase the number of available organs for liver transplantation. In 1984, Bismuth first reported the use of a reduced-size liver graft in pediatric liver transplantation, using a whole liver graft from a deceased donor to create a small functional graft to fit a pediatric recipient (Bismuth and Houssin 1984). This technique became popular in pediatric liver transplantation with excellent survival rates and significantly decreased pediatric waiting list mortality. When this technique is used, however, the remaining part of the liver mass is discarded. For this reason, the concept of "splitting" a whole liver graft to simultaneously transplant two recipients emerged and subsequently was performed successfully (Pichlmayr et al. 1988; Bismuth et al. 1989; Emond et al. 1990). Unlike reduced-size grafts, split liver transplantation (SLT) was initially characterized by higher mortality and complication rates (Broelsch et al. 1990). However, with the accumulation of experience, improved surgical techniques, and better donor and recipient selection, split grafts have been used more frequently worldwide.

For successful SLT, two functional grafts have to be created from a whole deceased donor liver. Since the first report of SLT in 1988 (Pichlmayr et al. 1988), deceased donor livers have been most commonly split into a smaller left lateral segment (LLS, segments II and III; 15–25 % of the liver) for a child and a larger right trisegment (RTS, segments I, IV, and V–VIII; 75–85 % of the liver) for an adult. The potential for SLT was further expanded to use two hemiliver grafts to transplant two adult recipients: a left lobe (segments I–IV; 30–40 % of the liver) and a right lobe (segments V–VIII; 60–70 % of the liver). While the procedure has shown a great success worldwide and could theoretically double the number of available organs, many challenges have precluded its more widespread use.

Donor Evaluation

Careful donor selection is essential to the success of SLT (Table 1). The upper donor age limit of the bipartition of a liver graft is between 40 and 50 years (Emre and Umman 2011). The donor liver function test ideally should be normal, but can be mildly elevated. When liver enzymes are elevated, as long as they show improvement before organ recovery, the liver can be used for SLT. However, since liver splitting can compromise donor quality, any additional negative factors are discouraged (Feng et al. 2006). High BMI, history of heavy alcohol use, and low platelet counts on donor admission could signal the presence of graft steatosis and fibrosis. Hypernatremia

Table 1 Donor selection criteria in split liver transplantation

Ideal split donor	Donor age < 40–50 years
	Liver function test (normal or mildly elevated)
	Serum sodium level < 160 mEq/L
	No or minimal inotropic support (hemodynamic stability)
	Normal macroscopic and microscopic appearance of the liver
Acceptable split donor	Mild macrosteatosis < 10–20 % in biopsy
	Mild inflammation in biopsy
	Elevated liver enzymes, but improving
	ICU stay before organ recovery > 5 days
	Serum sodium level > 160 mEq/L
	Obese donor (BMI > 30 m^2/kg)

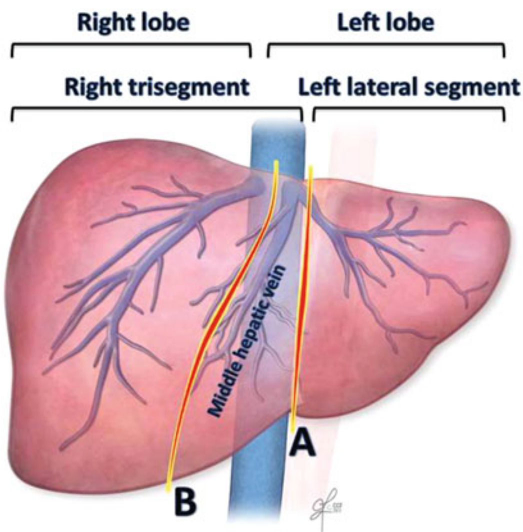

Fig. 1 Graft types used in split liver transplantation. Splitting at the falciform ligament yields left lateral segment and right trisegment grafts (**line A**). In hemiliver splitting for left lobe and right lobe grafts, the liver is split on the right side of the middle hepatic vein (**line B**)

(>160 mEq/L) and the use of inotropic support can be risk factors for a nonfunctioning split graft. Other compounding risk factors should be taken into consideration to determine whether the liver is splittable or not. These include estimated cold ischemia time, length of ICU stay of the donor, recipient MELD score, the degree of portal hypertension, and recipient functional status.

Direct evaluation by the donor team at the time of organ recovery is of utmost importance. If the donor liver does not look normal on visualization, a frozen section biopsy of liver is indicated. Pathological changes such as macrosteatosis, inflammation, fibrosis, and cholestasis are generally considered to be contraindications for splitting. However, if other donor and recipient factors are ideal, mild steatosis (<10–20 % macrosteatosis) or the presence of mild inflammation can be acceptable. Once the decision is made to proceed, the donor team must coordinate the recovery process with the recipient team to minimize cold ischemia time.

Estimation of Graft Size

Split graft size is an important factor in SLT. Splitting at the falciform ligament yields LLS and RTS grafts (Fig. 1, **line A**). The LLS is generally suitable for pediatric recipients. When a small infant is the recipient, graft-to-recipient weight ratio (GRWR: [liver graft weight ÷ recipient body weight] × 100) should not exceed 4–5 % to avoid large-for-size-related complications, such as open abdomen and vascular thrombosis. If this is the case, the LLS split graft has to be further reduced to avoid such problems (Kasahara et al. 2003). The RTS graft size, on the other hand, is in most instances large enough to avoid small-for-size-related graft dysfunction in adult recipients.

In hemiliver splitting for two adult-sized recipients, the liver is split on the right side of the middle hepatic vein (Fig. 1, **line B**). Determination of graft size is crucial to decide whether splitting is feasible and to minimize the possibility of small-for-size-related graft failure. Although the minimal graft size to meet recipient's metabolic demand in living donor liver transplantation is considered to be as small as a GRWR of 0.6–0.8 %, the minimal ratio remains unknown. SLT appears to require a higher GRWR to compensate for suboptimal graft quality related to longer cold ischemia time and donor hemodynamic instability associated with brain death. Accordingly, a GRWR of 1.0 % seems to be the minimal requirement in SLT to avoid early graft dysfunction (Lee et al. 2013).

Imaging studies are rarely available in SLT to estimate graft weight and evaluate donor liver anatomy. Therefore, this important surgical information is most often unknown until the time of organ recovery or after a liver is taken out of a deceased donor. Using the donor body surface area, whole liver volume (mL) can be estimated using equations 1072.8 $\times$ body surface area (m^2) $-$ 345.7 for Caucasians (Heinemann et al. 1999) and 706.2 $\times$ body surface area (m^2) + 2.4 for Asians (Urata et al. 1995). More simply, whole liver weight can be estimated as 2 % of donor body weight (Lee 2010). These estimated values can be divided into standard estimates for lobar distribution (35 % for the left lobe and 65 % for the right lobe) to estimate hemiliver graft size.

Recipient Evaluation

For successful SLT, recipient selection is as important as donor selection. In SLT using the LLS graft for pediatric recipients, graft-recipient size mismatch resulting in large-for-size complications should be avoided. When the recipient is an older child, the LLS graft might not be enough to provide adequate liver mass. In such an instance, the left lobe graft is necessary to achieve a GRWR $>$ 1.0 %. For the RTS graft, recipients can be chosen more liberally, similar to when a whole liver graft is used.

SLT for adults has the potential risk of small-for-size syndrome, particularly with hemiliver grafts. Generally, the best SLT recipients for a hemiliver graft are an adolescent or a small adult with minimal portal hypertension and/or a relatively low MELD score, particularly for the left lobe graft. Although a recipient with a high MELD score can be transplanted with a hemiliver split graft, the data are not available to support the routine use of hemiliver grafts for high-risk recipients (Nadalin et al. 2009; Hashimoto et al. 2014). When a recipient has significant portal hypertension, a larger right lobe graft is preferred in order to lower the risk of small-for-size syndrome. In addition to examining medical history, the severity of portal hypertension can be assessed using a triphasic CT scan or MRI (Aucejo et al. 2008). These imaging studies show the recipient's surgical anatomy and also can show portosystemic shunt, portal vein thrombosis, and stenosis of the celiac trunk, which are important pieces of surgical information. The management of portosystemic shunt is controversial (Ikegami et al. 2013). When recipients have a large spontaneous or surgical portosystemic shunt, the shunt can cause hypoperfusion of a transplanted split graft due to a steal phenomenon. In contrast, it also helps lower portal vein pressure to favorably accept a small partial graft that is damaged by portal hyperperfusion. Accordingly, a case-by-case assessment is important to determine whether to close shunts in recipients.

In addition to thorough donor and recipient selection, appropriate donor-recipient paring is crucial to achieve good outcomes in SLT. In adult SLT, split grafts are generally taken from larger donors and transplanted into smaller recipients. This graft-recipient paring enables the majority of recipients to achieve a GRWR $>$ 1.0 % (Hashimoto et al. 2014), representing a size advantage that helps avoid small-for-size syndrome.

Split Liver Transplantation Under MELD Allocation

The use of split grafts for high-risk recipients is controversial (Nadalin et al. 2009; Hashimoto et al. 2014). Under the philosophy of the "sickest first" MELD allocation, standard criteria donors who are suitable for bipartition are allocated to those recipients with a high MELD score who are generally unsuitable for SLT.

When a splittable donor becomes available, the most important factors determining whether to proceed with SLT are when a whole donor liver is deemed to be too large to fit a primary adult candidate or a small pediatric recipient is on the waiting list. SLT has proven to be a great benefit for pediatric candidates who usually need an LLS graft without compromising survival in adult recipients receiving the RTS graft (Maggi et al. 2015). It is equally important, however, that small adults who are often bypassed on the waiting list due to size mismatch can have more opportunities by SLT. For these recipients, split grafts can provide enough liver volume to tolerate portal hyperperfusion. The remaining split graft can be used for a candidate with minimal portal hypertension and a lower MELD score. This graft-recipient matching helps achieve excellent survival after SLT under the allocation system where the MELD score regulates transplant priority. However, such ideal matching is difficult to achieve on a routine basis, and this is why many centers underutilize or do not use split grafts, particularly when hemiliver splitting is indicated. According to the Cleveland Clinic experience from April 2004 to June 2012, 137 out of 1089 deceased donors (12.6 %) met the SLT criteria and were identified as suitable for splitting. However, among these splittable donors, only 38 (3.5 %) were used for SLT because suitable recipients were not available.

Sharing Patterns of Major Vessels and Bile Duct in Split Donors

An important technical challenge in SLT is a lack of consensus between transplant centers regarding surgical techniques, particularly sharing patterns of major vessels and bile ducts between two split grafts. The ideal sharing pattern was originally described by Bismuth in 1989 (Bismuth et al. 1989). The principle concept of this technique is to avoid multiple branches to be reconstructed in the recipient operation. Impeccable knowledge of surgical liver anatomy is essential to understand this sharing pattern. The left lobe frequently has a single branch of the portal vein, hepatic duct, and venous outflow that is a common channel of the left and middle hepatic veins, but multiple branches of the hepatic arteries often exist. The right lobe, on the other hand, often has a single right hepatic artery and multiple branches commonly seen in the venous drainage, hepatic duct, and portal vein. According to the sharing pattern by Bismuth, the left lobe retains the celiac trunk, and the right lobe retains the remaining major structures, including the common hepatic duct, main portal vein, and vena cava. Although typically the priority is for the primary recipient to keep necessary structures in the graft allocation, sharing should depend on actual donor anatomy and recipient needs. The final decision should be made with flexibility and agreement by both teams who each take one of the split grafts.

Donor Anatomical Variation

As long as both sides of the split grafts have a complete set of inflow and outflow vessels and biliary drainage, anatomical variations are not considered to be a contraindication to splitting. Recipient surgeons must decide on the division of these vital structures to make the liver graft safely usable in the recipients. The following are relatively common anatomical variants seen in organ recovery:

Hepatic Artery

Arterial variants are commonly seen in split organ recovery. Identification of the origin of the middle hepatic artery (A4: segment IV artery) is crucial. In LLS/RTS splitting, A4 can be the only blood supply to the medial segment of the RTS graft. If A4 arises from the left hepatic artery, it may need to be sacrificed. In the presence of the left accessory hepatic artery arising from the left gastric artery, retaining the celiac trunk with the left-sided graft helps keep the blood supply to all small branches from a single anastomosis. A right replaced hepatic artery from the superior mesenteric artery is the most commonly seen variant in the hepatic artery. In this instance, the artery can be taken with the superior mesenteric artery to be used as a patch for a wider anastomosis.

Portal Vein

Anatomical variants of the portal vein leading to multiple anastomoses or as a contraindication for splitting are uncommon. Trifurcation of portal branches is most commonly seen in about 20 % of the general population. The right anterior branch can arise from the left portal vein, but it is usually identified in the extrahepatic portion. As long as the left branch of the portal vein is transected distally to the origin of the right branch, this variant is not a contraindication to splitting. When the left-sided graft retains the main portal vein, the right-sided graft can be left with two separate portal vein branches. While not ideal, this situation is not a contraindication to splitting because conducting two portal vein anastomoses with or without a vein graft is feasible. When one of the right portal vein branches arises from the left intrahepatic portal branch, splitting may not be feasible. Such a portal variant is usually accompanied with a biliary anomaly that can be seen with an intraoperative cholangiogram.

Hepatic Vein

Since venous outflow is critical in determining functional graft size, ensuring perfect flow in the hepatic veins is essential in SLT. Most of the time, hepatic venous anatomy is unknown before split organ recovery. Since the left hepatic vein is almost always (92 %) dominant for the left lobe, the left lobe graft retaining both the left and middle hepatic veins usually promises optimal outflow. On the other hand, various anatomical variants are seen in the right and middle hepatic veins. In general, the right anterior segment (segments V and VIII) predominantly drains into the middle hepatic vein that is retained in the left lobe graft in a hemiliver split. Therefore, a significant (>5 mm) venous branches of segments V (V5) and VIII (V8) should be reconstructed with a vein graft to prevent severe graft congestion (refer to section "In Situ Hemiliver Split Technique"). When congestion occurs, the congested area does not fully function, and the amount of functional graft volume can be reduced, which may cause small-for-size syndrome. A significant branch of the inferior right hepatic vein (>5 mm) directly draining into the vena cava exists in 20–40 % of donors. When the vena cava is retained in the left lobe graft, this vein should be preserved and reconstructed in the recipient.

Bile Duct

Intraoperative cholangiogram should be routinely performed in split organ recovery to rule out any anatomical variant that renders the donor unsuitable for splitting, particularly in hemiliver split. For instance, an aberrant right hepatic duct arising from the cystic duct (2–3 %) increases the complexity of recipient surgery. If surgeons are not aware of such variant, it can cause serious complications in the recipient.

Ex Vivo vs. In Situ

Originally the development of SLT started with the ex vivo technique that splits the liver on the back table after conventional whole organ retrieval. The early experiences in the 1990s demonstrated the feasibility of this technique, which was followed by the first report of the in situ technique by Rogiers in 1995, who split the liver in a heart-beating deceased donor (Rogiers et al. 1995). Since then, two decades of experiences have proved that both techniques are equally effective and have been used with continual refinements. Although pros and cons of both techniques have been recognized, the decision whether to use the in situ or ex vivo technique is often made based on logistical issues, hemodynamic stability of the donor, and the surgeon's preference (Table 2).

Since the ex vivo technique does not require extra time before organ retrieval, it offers easier and better coordination with other organ teams. However, this technique potentially causes prolonged cold ischemia to perform the complex back table preparation. During ex vivo splitting, the liver is hardly immersed in cold preservation solution, so that the liver may not be preserved cold enough to prevent graft rewarming injury. Equally important is the risk of substantial bleeding and bile leakages from the cut surface of liver parenchyma. On the other hand, the in situ

Table 2 Comparisons of ex vivo vs. in situ splitting

	Ex vivo	In situ
Organ recovery time	Shorter	Longer
Donor hemodynamics in organ recovery	Same as regular organ recovery	Potentially unstable due to bleeding during splitting
Coordination with other organ teams	Easier	Harder
Cold ischemia	Longer	Shorter
Risk of rewarming injury on back table	Higher	Lower
Post-reperfusion bleeding	Potentially profuse	Minimal

technique requires prolonged time in organ recovery, which is not always possible due to donor hemodynamic instability and logistical challenges with other organ recovery teams. However, the in situ technique promises shorter cold ischemic time and better hemostasis after graft reperfusion.

In Situ Hemiliver Split Technique

Laparotomy and Hilar Dissection

After opening the abdominal cavity, the liver is visually and manually assessed to ensure that it is suitable for splitting. If the liver looks marginal, the liver should be biopsied, or the split procedure can be aborted at this point. Estimated weight of the liver should be notified to recipient teams. The left lobe is mobilized by dividing the left triangular, coronary, and gastrohepatic ligaments. When a left accessory hepatic artery is seen, it must be preserved. The right triangular and coronary ligaments are taken down to mobilize the right lobe. The hepatorenal ligament and bare area of the liver are dissected until the retrohepatic vena cava appears. The hepatocaval ligament does not need to be divided, unless the vena cava is kept with the left lobe graft. Although short hepatic veins of the left lobe are divided to detach the left caudate lobe from the vena cava, this step can be easily and safely done on the back table. Before hilar dissection and parenchymal transection, the supraceliac and infrarenal aortas should be isolated according to standard deceased donor techniques in case the donor becomes unstable.

What need to be done at the hepatic hilum are cholecystectomy, cholangiogram, and anatomical evaluation. After a standard cholecystectomy, the cystic duct is cannulated to perform cholangiogram to rule out anatomical variants that would make it not feasible to perform the split procedure. If cholangiogram is not available in the donor hospital, the common bile duct can be transected to probe the bile duct. The hepatic hilum is examined manually to delineate the arterial anatomy, particularly the location of arterial bifurcation and the presence of the right replaced hepatic artery. The bifurcation of the hepatic artery can be dissected free, but this step also can be safely done on the back table.

Preparation for Liver Hanging Maneuver

The hanging maneuver is used to isolate liver parenchyma from the vena cava and the hepatic hilum on the transection line. This technique facilitates hemostasis by elevating the liver, and more importantly, it guides donor surgeons to divide liver parenchyma straight down to the vena cava. The groove between the right and middle hepatic veins is dissected free to tunnel the tissue between the liver and retrohepatic vena cava. A Kelly clamp is vertically introduced along the anterior surface of the infrahepatic vena cava toward the groove to complete tunneling. After 4–5 cm of gentle blind dissection, the clamp appears at the groove, and an umbilical tape is pulled through this tunnel. An angled clamp is directly introduced into liver parenchyma at 0.5 cm above the bifurcation of the hepatic hilum and passed behind the hepatic hilum through liver parenchyma. The tip of the clamp appears at 0.5 cm below the bifurcation, and the umbilical tape is pulled back through liver parenchyma (Fig. 2). This technique has a minimal risk of major bleeding or bile

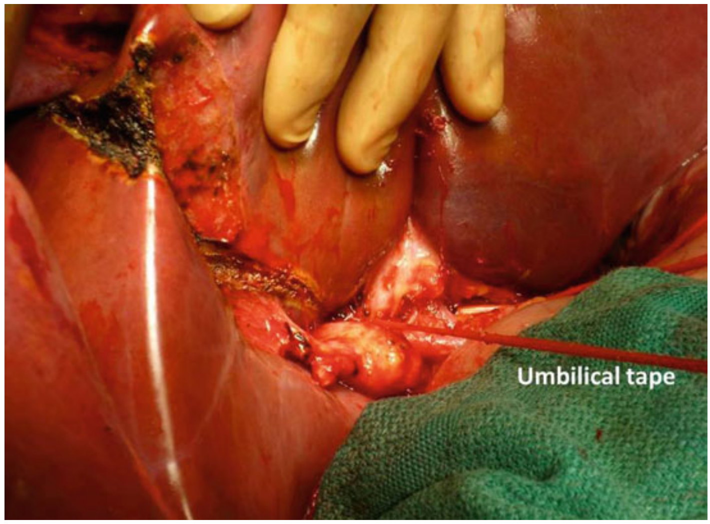

Fig. 2 Hanging maneuver in the in situ split technique. An umbilical tape is seen to isolate liver parenchyma from the vena cava and the hepatic hilum on the transection line

leakage because there are no major vessels or bile ducts in the area of liver parenchyma where the clamp passes through. Introducing a clamp along the cephalad margin of the hepatic hilum may cause serious bleeding or bile leakage if a tip of the clamp migrates into the hilar structures (Hashimoto and Fung 2013).

Parenchymal Transection

A transection line is marked by electrocautery along the Cantlie line. This line can be deepened from 0.5 to 1 cm since there is no important vascular structure or bile duct present. Because the transection line in hemiliver splitting is determined based on the anatomy of the middle hepatic vein, it is not necessary to confirm the demarcation line by a temporary hemihepatic inflow occlusion. Parenchymal transection can be done with any available methods at the donor hospital (clamp-crushing technique, CUSA, etc.). The Pringle maneuver is usually unnecessary. If major bleeding occurs and the donor becomes unstable, the liver surgeon should not hesitate to abort in situ splitting and proceed with cross clamping in coordination with the thoracic team. Then the liver can be split ex vivo after the liver is taken out. During parenchymal transection, small vessels can be cauterized, but larger vessels should be tied or clipped. Once the middle hepatic vein is identified, transection should be continued to stay on the right side of the middle hepatic vein until the V5 is identified. The V5 is tied proximally (on the middle hepatic vein) and clipped distally (on the right lobe side). Parenchymal transection is continued until the V8 is isolated and divided in the same manner. When the liver is split in situ, the degree of graft congestion in the anterior segment can be assessed during parenchymal transection. To prevent bleeding from small branches of the middle hepatic vein, a thin layer of parenchymal tissue should be left over the middle hepatic vein. To complete parenchymal transection, the both ends of the umbilical tape are pulled to give upward traction to facilitate the exposure and hemostasis. The liver is completely separated into the right and left lobes, and the anterior aspect of the retrohepatic vena cava is exposed.

Cross Clamp and Organ Retrieval

After coordinating with the thoracic team, the donor is systemically heparinized, and an infusion cannula is placed into the distal aorta. The supraceliac aorta is cross-clamped, and cold perfusion is initiated. The clips on the V5 and V8 are removed to better flush the anterior segment. The liver is subsequently taken out using the standard technique (Fig. 3). The donor surgeon must

Fig. 3 A liver graft after cold perfusion on the back table. The liver is already split in situ to yield left lobe and right lobe grafts

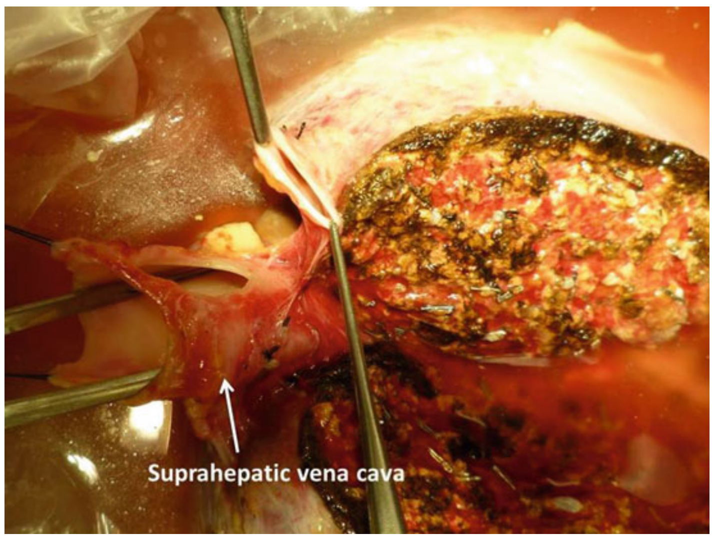

Fig. 4 Preparation of the venous outflow of the left lobe graft. The common channel of the left and middle hepatic veins is transected with a small vena cava patch

retrieve the iliac arteries and veins of good length and quality. When iliac grafts need to be shared with other organ teams, extra vessels must be taken from the carotid artery, subclavian artery/ vein, internal jugular vein, and innominate vein.

Back Table Preparation to Separate Vessels and Bile Duct

The liver is placed in a basin and perfused through the main portal vein with cold preservation solution. After the standard preparation of the vena cava, the common channel of the left and middle hepatic veins is transected with a small vena cava patch (Fig. 4). This technique ensures a good outflow of the left lobe without the need for a venoplasty, which is commonly needed in living donor liver transplantation. Short hepatic veins left undivided in situ are divided to detach the left caudate lobe from the vena cava. The main portal vein is dissected free all the way to its bifurcation. The left branch of the portal vein is dissected and transected 2–3 mm from the

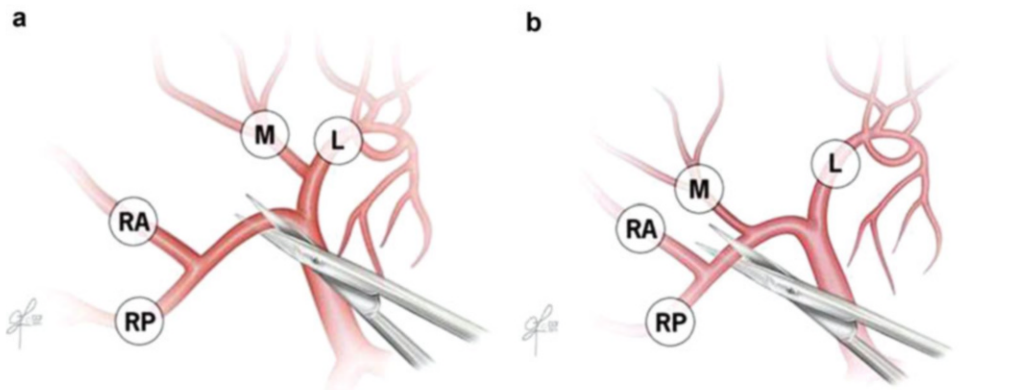

Fig. 5 Back table preparation for hepatic artery in hemiliver grafts. (**a**) When the middle hepatic artery arises from the left hepatic artery, the right hepatic artery is transected distally to the bifurcation. (**b**) When the middle hepatic artery arises from the right hepatic artery, the right hepatic artery is transected distally to the middle hepatic artery. *L* left hepatic artery, *M* middle hepatic artery, *RA* right anterior branch, *RP* right posterior branch

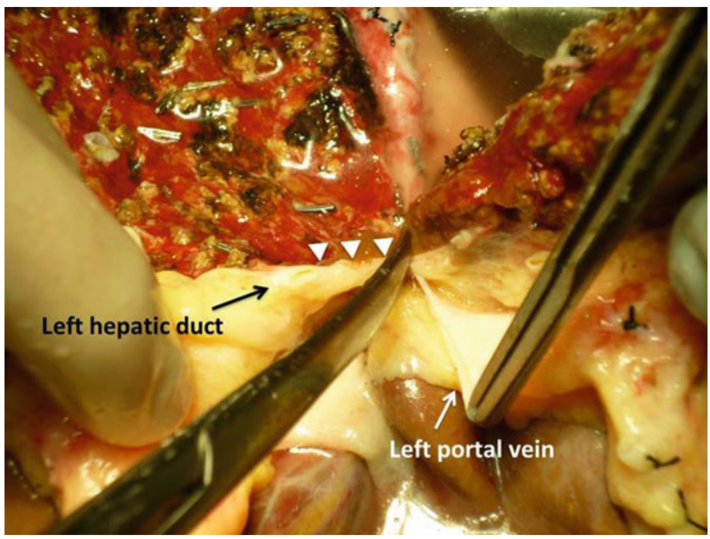

Fig. 6 Transection of the left hepatic duct and the hilar plate in hemiliver splitting. *White arrowheads* indicate the hilar plate

bifurcation. The caudate branch of the left portal vein usually needs to be divided. The defect on the main portal vein is sutured to close transversely. The defect should not be closed longitudinally because the risk of stenosis is high. The arterial component is dissected up to the bifurcation. However, the proper hepatic artery and the right and left hepatic arteries should not be skeletonized unnecessarily. The right hepatic artery is transected distal to the bifurcation (Fig. 5a). When the middle hepatic artery is arising from the right hepatic artery, the right hepatic artery is transected distal to the middle hepatic artery (Fig. 5b).

Finally, the hepatic duct and hilar plate are left at the hilum. Before bile duct division, both hepatic artery and portal vein branches have to be completely divided. The biliary system is probed through the common hepatic duct to confirm the location of the biliary bifurcation. The left hepatic duct with the hilar plate is sharply transected at 0.5 cm from the bifurcation (Fig. 6). The entire stump of the hilar plate should be oversewn because usually there are small caudate ducts. Preservation solution is injected into the left hepatic duct to check for leakage. At this point, the left lobe is ready for implantation.

Reconstruction of Tributaries of the Middle Hepatic Vein

To prevent venous congestion in the anterior segment, a new middle hepatic vein is created on the cut surface of the right lobe graft. A donor iliac vein graft is prepared, and its distal side is anastomosed in an end-to-end or end-to-side fashion to the V5 and V8 of significant size. The proximal end of the vein graft is directly anastomosed to the defect on the vena cava where the common channel of the left and middle hepatic veins was located (Fig. 7). When there are no V5 and V8 of significant size, the defect on the vena cava is closed with a vein graft patch. The defect of the left hepatic duct on the main hepatic duct is sutured to close transversely. The entire stump of the right hilar plate should be oversewn. Preservation solution is injected into the common hepatic duct to check for leakage. Finally, the right lobe graft is ready for implantation.

In Situ Split Technique for Left Lateral Segment and Right Trisegment Grafts

Hilar Dissection and In Situ Splitting

After visual and manual assessment of visceral organs, the left lobe is mobilized in the same manner as hemiliver splitting. If there is a left accessory hepatic artery, it must be preserved. The division of the Arantius ligament allows the surgeon to have better approach to the left hepatic vein. At this stage, the left hepatic vein does not need to be encircled.

The hepatic hilum is examined manually to delineate the arterial anatomy. Intraoperative cholangiogram is not mandatory, but can be done after cholecystectomy. Because hilar dissection can be safely done on the back table, extensive dissection of the hilum can be omitted at this point.

On the surface of the liver, a transection line is marked by electrocautery on the right side of the falciform ligament. The Glissonian triads to the medial segment are tied and divided. Although the medial segment often becomes ischemic after dividing its inflows, the ischemic area does not need to be resected. For parenchymal transection, inflow occlusion (the Pringle maneuver) is not necessary. Vessels are cauterized, tied, or clipped in the same fashion as described in the hemiliver split technique. After liver parenchyma is completely separated into the left lateral segment and right trisegment grafts, the liver is taken out of the donor using a standard cold dissection technique (Fig. 8).

Back Table Preparation

After the standard preparation of the vena cava, the left hepatic vein is transected with a small

Fig. 7 The right lobe graft with a new middle hepatic vein. The iliac vein graft is used to drain the anterior segment

Fig. 8 Appearance of the liver split in situ to the left lateral segment and right trisegment grafts

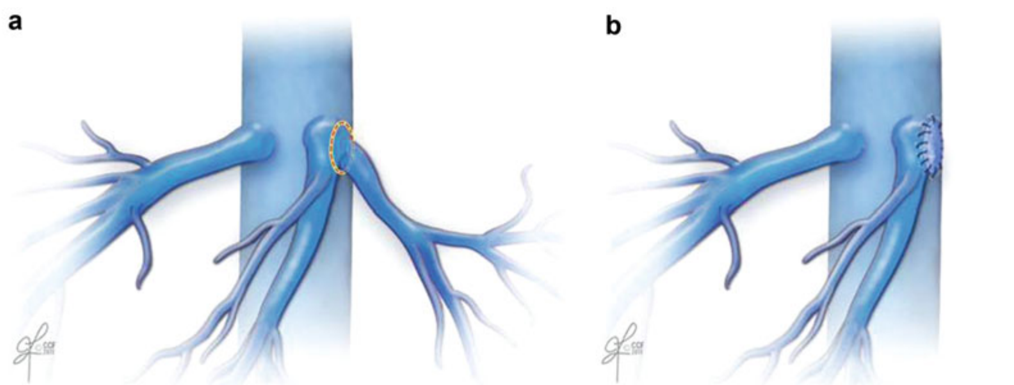

Fig. 9 Transection of the left hepatic vein in the left lateral segment graft. (**a**) The left hepatic vein is transected with a small patch of the vena cava and the middle hepatic vein. (**b**) The defect on the vena cava and the middle hepatic vein is closed with a venous graft patch to prevent stenosis of the middle hepatic vein

venous patch of the vena cava and the middle hepatic vein to secure sufficient length of a venous cuff to the LLS graft (Fig. 9a). The left branch of the portal vein is isolated and divided, and the defect on the main portal vein is sutured to close transversely in the same fashion as described in the hemiliver split technique. The right hepatic artery is transected distal to the bifurcation. The A4 should be kept with the RTS graft to secure arterial supply to the medial segment. However, it can be sacrificed if it arises from the left hepatic artery.

After transecting the artery and portal branches, the biliary system is probed to confirm the biliary anatomy from the stump of the common bile duct. The left hepatic duct and hilar plate are sharply transected on the line of parenchymal transection. The entire stump of the hilar plate should be oversewn to prevent bile leak. Preservation solution is injected into the distal left hepatic duct to check for leakage. At this point, the LLS graft is ready for implantation.

A piece of donor vein graft is used to patch the defect on the vena cava and the middle hepatic vein (Fig. 9b). A primary closure of the defect is not recommended because it can cause serious impairment of venous outflow of the middle hepatic vein. The defect of the left hepatic duct on the common hepatic duct is oversewn. Preservation solution is injected into the common bile duct to check for leakage. Finally, the RTS graft is ready for implantation.

Ex Vivo Split Technique

In the ex vivo split technique, a whole liver is first retrieved in a standard fashion. As soon as the liver is assessed visually and manually, recipient teams should be notified of the estimated liver weight. If available, intraoperative cholangiogram can be performed to delineate biliary anatomy before cross clamping. On the back table, vessels and bile duct are divided as described in the section of the in situ split technique. Parenchymal transection can be performed by sharp transection by a surgical knife or clamp-crushing technique. Decent-sized vessels and bile ducts on the cut surface should be tied or sutured to minimize bleeding after graft reperfusion. During back table preparation, the liver should be immersed in cold preservation solution to avoid rewarming of the liver.

Recipient Surgical Techniques

LLS Grafts

In pediatric recipients receiving the LLS graft, total hepatectomy is performed by preserving the native vena cava. Because the LLS graft usually retains the celiac trunk but not the main portal vein, the native portal vein should be left as long as possible. To achieve excellent venous outflow in small infants, a vertical cavotomy from the common orifice of the hepatic veins needs to be made to create a triangle-shaped large caval orifice (Emond et al. 1993). Because the graft hilar structures locate laterally in the right side of the abdomen, adequate redundancy is necessary in portal vein anastomosis to prevent stenosis. Biliary reconstruction is usually performed with hepaticojejunostomy with Roux-en-Y limb. When the native bile duct is available, a duct-to-duct anastomosis can be done with comparable outcomes to hepaticojejunostomy.

RTS Grafts

Because the RTS graft usually retains the entire vena cava, caval reconstruction can be done with either the piggyback or the standard technique. For arterial reconstruction, the native hepatic arterial branch should be preserved as long as possible in case the graft right hepatic artery is small. Sometimes, microsurgical technique is necessary to safely perform the anastomosis. The medial segment often looks ischemic due to the lack of adequate inflow (Fig. 10). However, such change is not associated with a higher risk of bile leak or parenchymal necrosis. Therefore, resection of the ischemic parenchyma is not required.

Hemiliver Grafts

As seen in other types of partial grafts, venous outflow is important to successful left lobe SLT. Since the size of the hemiliver donor is usually larger than the recipient, the donor venous orifice (the common channel of the left and middle hepatic veins with a small caval patch) can be directly anastomosed to the recipient caval orifice that is created by all three hepatic veins merged into one large orifice. This technique promises perfect venous outflow of the left hemiliver graft. The native portal vein and common hepatic duct should be left long because the main branch of the portal vein and hepatic duct are not retained with the left lobe graft.

In the right lobe graft, caval anastomosis can be done with either the piggyback or the standard technique. When the vena cava is retained with the right lobe graft, excellent venous outflow almost always can be achieved with a new middle hepatic vein draining into the donor vena cava (Fig. 11). When the vena cava is not retained with the right lobe, a complex venous reconstruction may be needed to avoid graft venous congestion as seen in living donor liver transplantation. Portal and biliary reconstructions can be done in

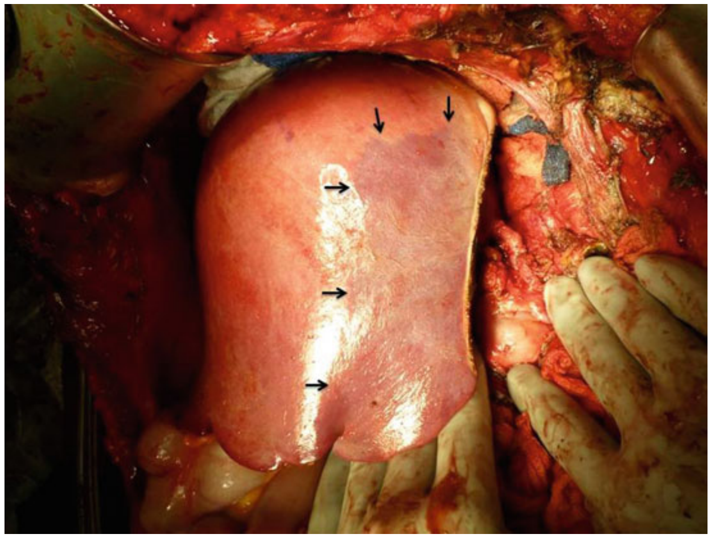

Fig. 10 Ischemic area of the medial segment in the right trisegment graft after implantation (*black arrows*)

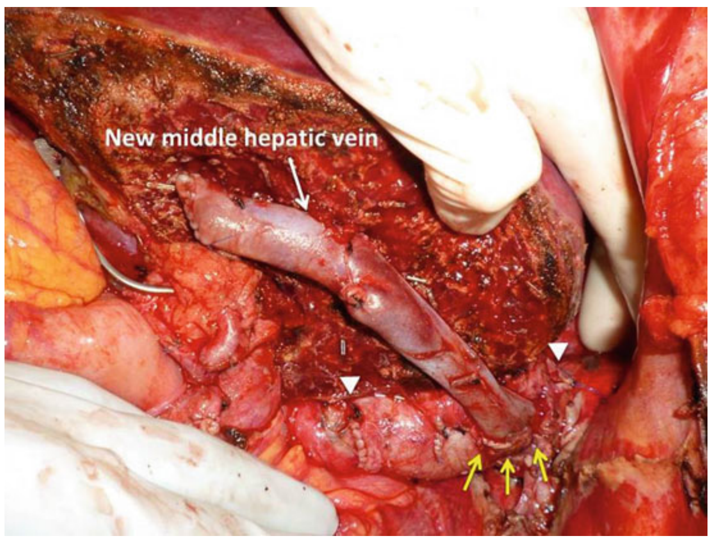

Fig. 11 The right lobe graft after implantation. A new middle hepatic vein created on the cut surface of the graft drains the anterior segment into the donor vena cava (*yellow arrows*). *White arrowheads* indicate caval anastomoses. The graft is transplanted in the standard caval interposition technique

the same fashion as whole liver transplantation. For arterial anastomosis, the native hepatic artery should be left long as described in the technique for the RTS graft.

Because excessive portal flow into the small partial graft can cause arterial insufficiency via hepatic arterial buffer response, the hemiliver graft in adults has a high risk of small-for-size syndrome, particularly when graft size is marginal (GRWR < 1.0 %), and the recipient physiology is characterized by severe portal hypertension. Portal venous pressure and flow volume can be directly measured to assess the severity of portal hyperperfusion. If necessary, surgeons should have a low threshold to modify portal inflow the split graft of marginal size (Boillot et al. 2002). Splenic artery ligation, splenectomy, and hemi-portocaval shunt are well-known techniques for portal inflow modification. Of these, the use of hemi-portocaval shunt is controversial due to the risk of portal steal phenomenon (Lee 2015).

Outcomes

LLS/RTS Grafts

In the last two decades, SLT has been widely observed, particularly for the child/adult combination with LLS and RTS grafts. However, the activity of this technique still accounts for less than 5 % of the total number of liver transplants in the United States and even fewer in Europe. There is no doubt that SLT has helped decrease liver transplant waiting list mortality in the pediatric population. It is equally important that the survival after pediatric SLT is equivalent or even superior to whole liver transplantation. In contrast to the excellent pediatric outcomes with LLS grafts, the outcome for the adult population receiving the RTS graft has been controversial (Mallik et al. 2012). Due to the technical complexity, the rates of biliary and vascular complications can be as high as 40 % and 25 %, respectively. Despite the high risk of surgical complications, the long-term survival of SLT recipients using the RTS graft is satisfactory (Doyle et al. 2013). Under favorable conditions such as short cold ischemia (< 8 h), nonurgent recipient status, and young donor age, outcomes for the RTS graft are promising. Nowadays, experienced centers no longer consider the RTS graft to be marginal (Maggi et al. 2015).

Hemiliver Grafts

Because experience with hemiliver SLT for two adult recipients is limited, its routine use remains controversial, particularly in countries where MELD-based allocation regulates organ distribution. Further, technical and logistical challenges are significant in precluding the efficient diffusion of this technique. A recent Italian multicenter study has shown that hemiliver SLT in adults had significantly inferior 5-year survival compared to whole liver transplantation (63 % vs. 83 %) (Aseni et al. 2014). However, under certain circumstances, the long-term survival of the hemiliver graft is equivalent to whole liver transplantation or living donor liver transplantation (Broering et al. 2005; Zambelli et al. 2012; Lee et al. 2013; Hashimoto et al. 2014). Biliary complications are the most common surgical issue in hemiliver SLT with incidence as high as 30–40 %. Vascular complications are not as frequent as biliary complications, but can be experienced at a rate as high as 20 %. According to the Cleveland Clinic experience, biliary complications were more frequently seen in hemiliver SLT than whole liver transplantation (32 % vs. 11 %), but generally could be managed by endoscopic or radiologic intervention and did not affect long-term survival (Hashimoto et al. 2014).

Ethical Aspect of Split Liver Transplantation

Creating two extended criteria split grafts from one standard criteria whole liver has been a matter of ethical debate (Vulchev et al. 2004; Collett et al. 2008). Since SLT per se is a risk factor for graft failure, especially when hemiliver grafts are used in adults, we often come up with a question about the pros and cons of SLT compared to waiting for a subsequent liver offer of smaller size that could be wholly transplanted. Although SLT has faced logistical challenges and less favorable outcomes, it gives recipients more opportunities to receive a life-saving liver transplant. While concerns exist about the general application of this highly complex surgical technique, which uses a potentially high-risk organ, SLT is expected to achieve comparable or even superior survival to whole liver transplantation. By addressing known challenges and gaining successful experience, sharing deceased donor livers through SLT is possible even with other transplant centers that generally have different strategies. To justify more frequent use of SLT, further accumulation of successful outcomes and general consensus between centers is necessary. Finally, it should be noted that recipients have the unequivocal right to refuse an offer of a split graft. With complete and accurate information, thorough discussion of the risks and benefits of SLT with the liver transplant candidates should take place at the time of evaluation, listing, and organ offer.

Conclusion

SLT is a valid technique to increase the opportunity for both children and adults who are in need of life-saving liver transplantation. After more than two decades of experience, we know that this highly complex surgical technique is feasible and can achieve excellent outcomes under certain circumstances. Despite differences in surgical techniques among centers, various techniques work well, almost equally, including ex vivo vs. in situ, pediatrics vs. adults, and split vs. whole liver. Although technical, logistical, and ethical challenges are still not completely overcome, the transplant community should be encouraged to use split grafts to address the current severe donor shortage.

Cross-References

▶ Donor Operation
▶ History of Liver and Other Splanchnic Organ Transplantation
▶ Live Donor Liver Transplant
▶ Orthotopic Liver Transplantation: Complications
▶ Orthotopic Liver Transplantation: Surgical Techniques

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