PICTORIAL ESSAY

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Intraoperative Doppler sonogram in pediatric liver transplants: a pictorial review of intraoperative and early postoperative complications

A. Luana Stanescu[1] · Shawn E. Kamps[1] · André A. S. Dick[2] · Marguerite T. Parisi[1,3] · Grace S. Phillips[1]

Abstract

A spectrum of vascular complications can be seen in pediatric liver transplant patients, including occlusion and hemodynamically significant narrowing of the vessels that provide inflow to or outflow from the graft. Intraoperative Doppler ultrasound (US) has the potential benefit of identifying vascular complications in pediatric liver transplant patients prior to abdominal closure. Importantly, intraoperative Doppler US can be used as a problem-solving tool in situations such as position-dependent kinking of the portal or hepatic veins, or in suspected vasospasm of the hepatic artery. Furthermore, this technique can be used for real-time reassessment after surgical correction of vascular complications. This pictorial review of intraoperative Doppler US in pediatric liver transplant patients illustrates normal findings and common vascular complications, including examples after surgical correction, in the perioperative period.

Keywords Children · Doppler · Intraoperative · Liver · Transplantation · Ultrasound

Introduction

Liver transplantation is a potentially life-saving procedure for children with liver failure, liver cancer or metabolic liver disease. Pediatric liver transplant recipients are at greater risk for vascular complications compared to adults [1]. In addition, children more commonly receive technical variant allografts, such as reduced left hepatic

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✉ Grace S. Phillips
grace.phillips@seattlechildrens.org

1 Department of Radiology, Seattle Children's Hospital,
University of Washington School of Medicine,
4800 Sand Point Way NE
Seattle, WA 98105, USA

2 Department of Surgery, Section of Pediatric Transplant,
Seattle Children's Hospital
University of Washington School of Medicine,
Seattle, WA 98105, USA

3 Department of Pediatrics, Seattle Children's Hospital
University of Washington School of Medicine,
Seattle, WA 98105, USA

lobe, reduced left lateral segment or split liver, which alter normal liver anatomy. Intraoperative ultrasound (US) of the liver transplant has the potential advantage of identifying vascular complications that may be addressed prior to abdominal closure [2–5]. Intraoperative US may be performed in the operating room at the time of transplantation, as well as during surgical exploration or vascular revision in the immediate post-transplant period after a vascular complication has been identified by bedside US. In this pictorial review, we illustrate the normal sonographic intraoperative appearance of the liver transplant vasculature as well as common intraoperative and early postoperative complications. This review was approved by our institutional review board.

Types of transplant allografts

In infants and small children, cadaveric whole allografts or technical variants such as left lateral segments (Couinaud segments II and III) or reduced left lobes are used for transplantation. Living donor left lateral segment (Couinaud segments II and III) or left lobe (Couinaud segments II, III and IV) grafts can also be used. After recipient hepatectomy, the graft is positioned in situ with end-to-end hepatic arterial

and portal vein anastomoses. Arterial or venous grafts for the hepatic artery and portal vein, respectively, may be employed, such as in cases of donor and recipient vessel size mismatch. The hepatic vein anastomosis is made either using the piggyback or bi-caval technique. At our institution, a piggyback anastomosis is frequently employed between the donor and native inferior vena cavas. Anomalous hepatic veins, which may be encountered in technical variants along the cut edge, are typically small in caliber and are usually tied off at the time of surgery. The biliary anastomosis is performed end-to-end to a recipient biliary duct when feasible, or to a jejunal loop using a Roux-en-Y technique.

Doppler technique

At our institution, the routine use of intraoperative Doppler sonography was implemented for pediatric liver transplant patients in October 2006. In addition, routine postoperative Doppler examinations are also performed on postoperative days 1 and 4. Additional postoperative imaging is guided by the patient's clinical course.

For intraoperative imaging, an 8-5 MHz curvilinear transducer is used. The sterile intraoperative probe cover and gel are passed to the scrub nurse. The technologist holds the probe while the scrub nurse applies the gel to the inside of the probe cover. The technologist then places the transducer head into the probe cover. The technologist assists in covering an adequate length of the transducer's cord to maintain the sterile field. At our institution, saline (as opposed to gel) is instilled into the operative field and, using the liver as an acoustic window, the surgeon guides the transducer while the US technologist optimizes the machine settings. The radiologist interprets the images in real time in the operating room. Every attempt is made to optimize technical parameters such as angle correction and to appropriately align the sample volume box with the vessel, although this is at times difficult in the operative setting. While there are subtle variations in technique among our three transplant surgeons, the hepatic artery, portal vein and hepatic veins/outflow track are routinely interrogated. If a vascular complication is identified, repeat intraoperative imaging is generally performed after surgical correction.

For postoperative imaging, the patient is imaged either in the supine or decubitus positions, in a fasting state, with breath-holding when possible. Patients are not routinely sedated for US examinations. A 5 or 9 MHz curvilinear transducer is used, depending on the size of the patient. Gray-scale imaging is usually performed first of the graft in the transverse and longitudinal planes to evaluate the parenchyma, biliary tree and vessels. The

hepatic artery, portal vein and hepatic veins are imaged with color Doppler with spectral waveform analysis. Static images as well as cine clips are typically saved for interpretation and documentation.

Description of normal waveforms

A normal hepatic artery waveform is characterized by a sharp arterial upstroke and continuous flow throughout diastole (Fig. 1). A normal hepatic artery resistive index, as defined by (peak systolic velocity-peak diastolic velocity)/peak systolic velocity measures between 0.50 and 0.80. However, for up to 72 h in the immediate postoperative period, the resistive index may be higher than 0.80 due to the hepatic artery buffer response, whereby hepatic artery flow diminishes in response to hyperdynamic portal venous flow [6, 7]. Jamieson et al. [8] determined that the incidence of complications was low for a resistive index of less than 0.95 on postoperative day 1. Conversely, a tardus parvus waveform can be seen in the immediate postoperative period due to edema at the anastomosis [9] or vasospasm [10], which should be considered when interpreting this finding in the absence of an upstream thrombus. A slight blunting of the systolic peak and a systolic double peak, found in 28% of pediatric patients on postoperative day 1, had no association with hepatic artery complications [8].

The portal vein normally demonstrates phasic and antegrade (hepatopetal) flow (Fig. 2), with a velocity greater than 10 cm/s [11]. As mentioned above, increased portal venous flow is often seen immediately after transplantation [7, 12]. In addition, turbulence may be normally seen near the anastomosis in the immediate postoperative period [13].
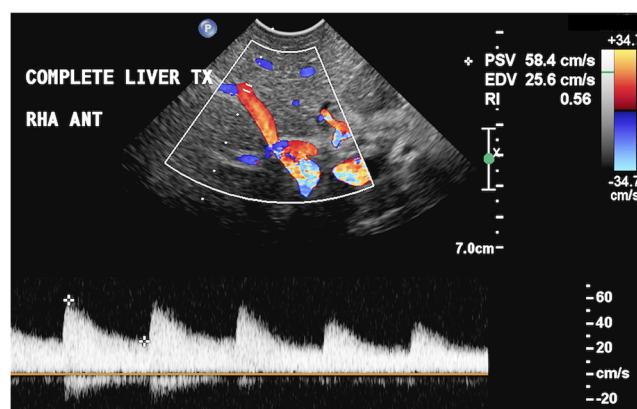

Fig. 1 Normal arterial waveform. Intraoperative interrogation of the anterior branch of the right hepatic artery (RHA ANT) in a 13-year-old boy undergoing whole liver transplantation for Alagille syndrome reveals normal sharp arterial upstroke and flow throughout diastole. Resistive index is 0.56, which is within the expected normal range of 0.50 to 0.80. *EDV* end diastolic velocity, *PSV* peak systolic velocity, *RI* resistive index
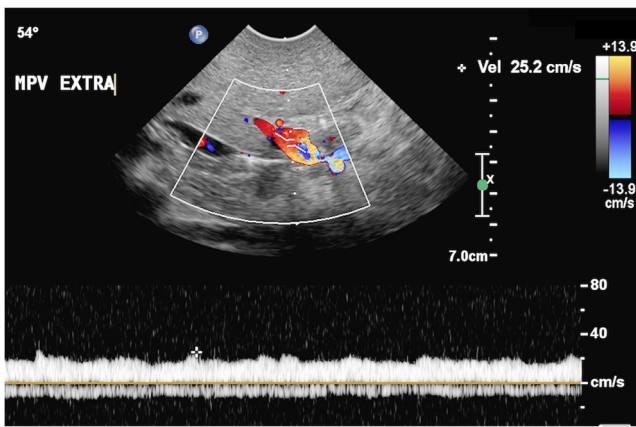
Fig. 2 Normal portal vein waveform. Intraoperative interrogation of the extrahepatic portion of the main portal vein (MPV EXTRA) in an 8-month-old girl undergoing liver transplantation for biliary atresia shows normal phasic antegrade (hepatopetal) flow. Intrahepatic portal vein velocities are normally greater than 10 cm/s. *Vel* velocity

Intraoperative interrogation of the hepatic veins normally shows a multiphasic waveform that reflects right heart pressures throughout the cardiac cycle (Fig. 3).

Hepatic artery complications and considerations

Hepatic artery thrombosis

Hepatic artery thrombosis is a serious complication that can threaten the viability of the graft. Isolated hepatic artery thrombosis is associated with acute hepatic necrosis and ischemic biliary complications such as biliary leaks or strictures [1, 14]. Furthermore, when hepatic artery thrombosis is identified within the first week after transplantation, the patient
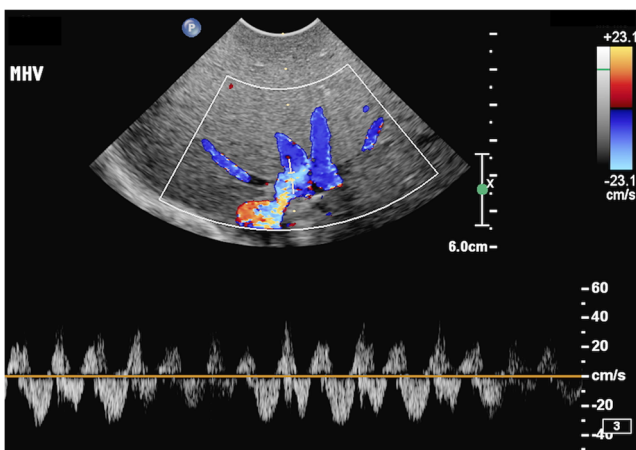

Fig. 3 Normal hepatic vein waveform. Intraoperative interrogation of the middle hepatic vein (MHV) near the hepatic vein confluence in an 8-month-old girl undergoing liver transplantation for biliary atresia shows a normal, multiphasic waveform

receives the highest priority for relisting if the thrombosis cannot be corrected surgically. Therefore, timely diagnosis of hepatic artery thrombosis is essential.

The incidence of early hepatic artery thrombosis in pediatric liver transplants has been reported in recent series as being between 4.9% and 8.3% [8, 15, 16]. Risk factors associated with hepatic artery thrombosis include prolonged graft cold ischemic time, use of split or segmental grafts, lower body weight and higher graft to recipient weight ratio, use of vascular grafts, and transplantation for malignancy such as hepatoblastoma [9, 15, 17–19]. To some degree, the risk of hepatic artery thrombosis may be mitigated by microvascular surgical technique and a postoperative anticoagulation protocol [20].

On Doppler sonography, hepatic artery thrombosis manifests as the absence of color Doppler flow and loss of the arterial signal (Fig. 4). A monophasic, high resistance waveform may be seen proximal to the thrombus. If the thrombus is nonocclusive, a low amplitude, tardus parvus waveform may be seen distal to the thrombus. Hepatic artery thrombosis may be addressed at the time of initial surgery by thrombectomy.

Hemodynamically significant hepatic artery narrowing

Hepatic artery stenosis, which most commonly occurs at the anastomosis, is considered a later postoperative complication. Several other entities, including partial thrombosis, recipient to donor vessel size mismatch, vessel kinking and vasospasm may occur in the intraoperative periods with resultant hemodynamically significant hepatic artery narrowing, mimicking hepatic artery stenosis. On Doppler sonography, luminal narrowing of 50% or greater and turbulent, high-velocity flow suggest a hemodynamically significant narrowing. Distal to the narrowed segment, a tardus parvus waveform may be demonstrated. Importantly, hemodynamically significant hepatic artery narrowing may be clinically occult at the time of surgery, without changes in blood pressure or the surface color of the liver transplant [21]; therefore, intraoperative sonographic diagnosis plays a potentially important role in early diagnosis. The treatment for hemodynamically significant narrowing of the hepatic artery depends on the underlying cause. For example, in the case of partial thrombosis, treatment consists of thrombectomy. In the setting of recipient to donor vessel size mismatch or vessel kinking, revision of the anastomosis (Fig. 5) or placement of a graft (Fig. 6) may be necessary. In cadaveric grafts, a portion of the donor iliac artery and vein are typically included with the procured liver graft in case they are needed for construction of an interposition graft for the hepatic artery and portal vein, respectively.
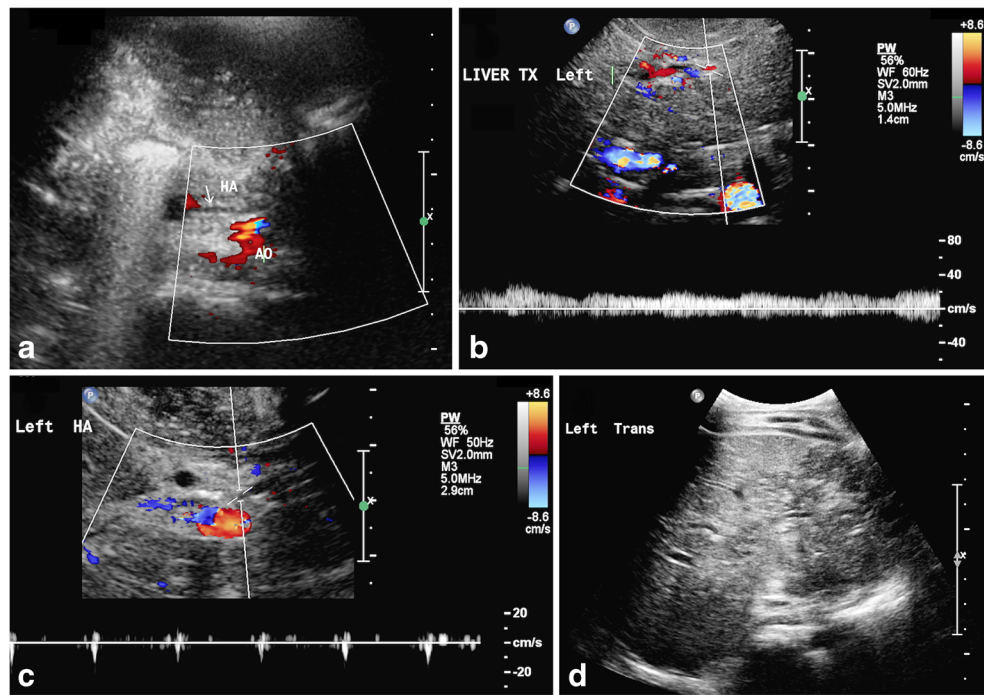
Fig. 4 Hepatic artery thrombosis. Color Doppler evaluation (**a**) of the extrahepatic artery in a 3-year-old boy who underwent liver transplantation for metabolic liver disease shows absence of color flow (*arrow*) on postoperative day 4. An abnormal tardus parvus waveform is interrogated in the left hepatic artery (**b**), with blunting of the systolic peak and abnormally high diastolic flow. Subsequent intraoperative Doppler interrogation (**c**) of the left hepatic artery after thrombectomy on postoperative day 4 after liver transplantation shows abnormal low amplitude, monophasic arterial waveform. Follow-up sonogram at the bedside on postoperative day 5 after transplantation (**d**) shows heterogeneity of the liver transplant consistent with infarcts. Doppler evaluation of the left hepatic artery (not shown) showed absence of color Doppler flow, consistent with recurrent hepatic artery thrombosis. The patient was emergently relisted and had retransplantation. *Ao* aorta, *HA* hepatic artery

The use of papaverine intraoperatively can assist in the differentiation between vasospasm and other potential causes of hepatic artery narrowing (Fig. 7). Papaverine decreases vasospasm of the hepatic artery and improves inflow. Lack of an appropriate response to papaverine in patients with diminished hepatic artery inflow at the time of transplantation may indicate a need to either revise the hepatic artery anastomosis or create a hepatic artery graft.

In the perioperative period, external compression of the hepatic artery from fluid collections or a tight intra-abdominal cavity can also result in hemodynamically significant hepatic artery narrowing (Figs. 8 and 9). In the case of a tight abdomen, intraoperative Doppler can assist in the critical decision-making of whether abdominal closure is feasible at the time of transplantation by dynamic assessment of the hepatic artery before and after attempted abdominal closure.
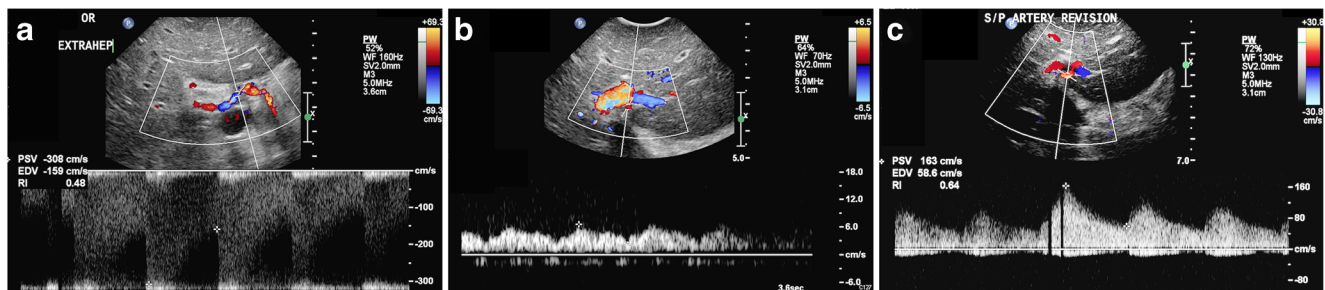

Fig. 5 Hepatic artery revision for hemodynamically significant narrowing. Intraoperative Doppler interrogation of the extrahepatic portion of the hepatic artery in a 17-year-old girl undergoing liver transplant for portal hypertension related to treatment for Wilms tumor as an infant (**a**) shows abnormally turbulent, high velocity flow. Intraoperative interrogation of the left hepatic artery (**b**) shows an abnormal tardus parvus, low amplitude waveform. While no kink or thrombus was identified, after revision of the hepatic artery anastomosis, there is improvement in the left hepatic artery waveform (**c**), with a sharper peak and normal resistive index of 0.64. *EDV* end diastolic velocity, *PSV* peak systolic velocity, *RI* resistive index
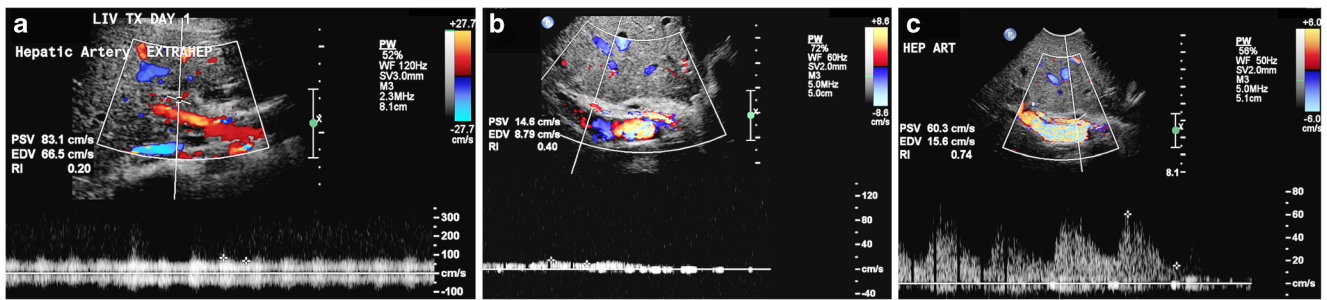
Fig. 6 Hepatic artery graft. Doppler interrogation at the bedside of the extrahepatic portion of the hepatic artery in a 14-year-old girl who received a liver transplant for Crigler-Najjar disease (**a**) on postoperative day 1 after transplantation shows abnormal low amplitude and tardus parvus waveform suggesting a proximal narrowing. Intraoperative Doppler evaluation (**b**) later that day confirmed abnormal low flow. Donor-recipient vessel size mismatch was suggested by intraoperative visual inspection and difficulty passing a dilator. After placement of an interposition donor iliac artery graft, repeat intraoperative Doppler sonogram (**c**) demonstrated improved arterial flow with a normal waveform. *EDV* end diastolic velocity, *HEP ART* hepatic artery, *PSV* peak systolic velocity, *RI* resistive index
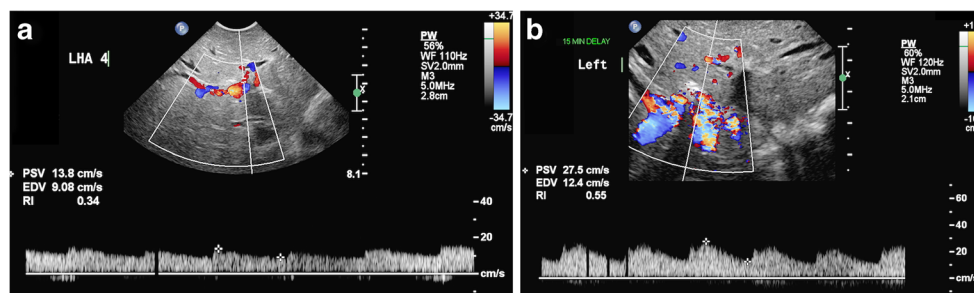

Fig. 7 Papaverine effect. Intraoperative Doppler interrogation of the left hepatic artery before (**a**) and after (**b**) the administration of papaverine in a 10-year-old boy who received a liver transplant for Crigler-Najjar type 1 shows improvement in the hepatic artery waveform with a sharper upstroke and normalization of the resistive index suggesting vasospasm, although the systolic peak remains blunted. *EDV* end diastolic velocity, *LHA* left hepatic artery, *PSV* peak systolic velocity, *RI* resistive index

Splenic artery steal

Splenic artery steal is a rare complication in which there is diminished hepatic arterial inflow (Fig. 10). Splenic artery steal is typically seen in liver transplant patients with concomitant hypersplenism. The sonographic diagnostic criteria for splenic artery steal are not firmly established [22]. Uslu et al. [23] found that hepatic artery resistive indices were statistically lower at the time of diagnosis of splenic artery steal, although a wide range was noted. A systematic review by Li et al. [24] found that 84.1% of patients from eight studies had elevated hepatic artery resistive indices. If splenic artery steal is suspected at the time of transplantation, intraoperative evaluation of the hepatic artery inflow before and after clamping the splenic artery can be performed, so that either the splenic
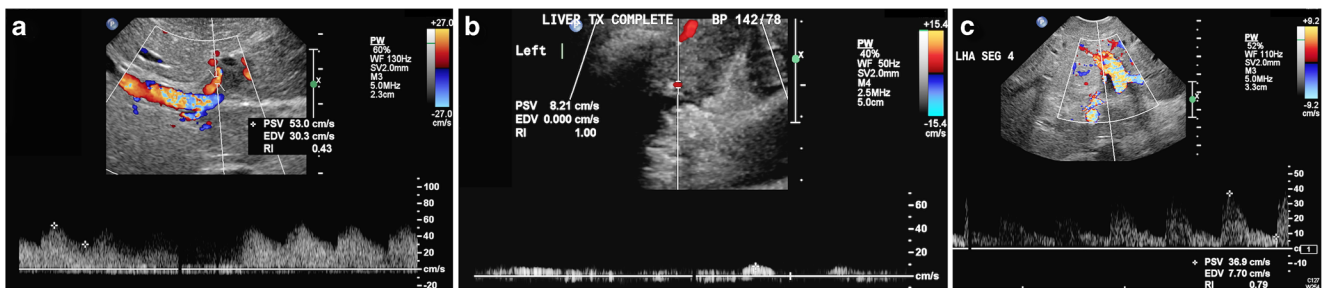

Fig. 8 Hepatic artery compression, case 1. Initial intraoperative Doppler interrogation of the left hepatic artery in a 10-year-old girl who received a liver transplant for progressive familial intrahepatic cholestasis type 1 (**a**) shows a normal arterial waveform. Subsequent interrogation at the bedside on postoperative day 1 (**b**) shows minimal flow, suggesting either thrombosis or external compression of the hepatic artery. The patient underwent surgical exploration. Intraoperative Doppler sonogram (**c**) at the time of exploration shows restoration of a normal arterial waveform with the abdomen open. No thrombus was found, suggesting that the prior findings were related to external compression. *EDV* end diastolic velocity, *LHA* left hepatic artery, *PSV* peak systolic velocity, *RI* resistive index
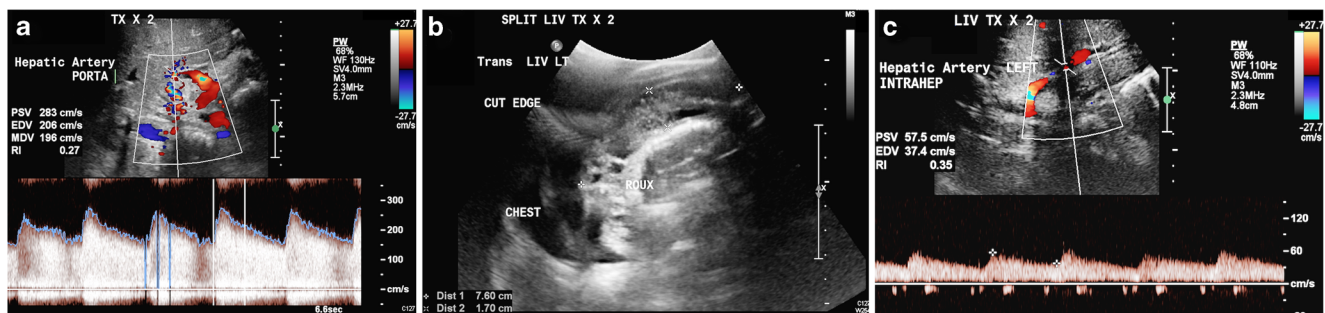
Fig. 9 Hepatic artery compression, case 2. Doppler interrogation of the extrahepatic portion of the hepatic artery on postoperative day 3 in a 3-year-old boy who received a liver transplant for metabolic liver disease (a) shows high velocity and turbulent flow suggesting hemodynamically significant narrowing. Complex fluid collection was noted near the porta hepatis along the cut edge of the split transplant graft (b). After exploration and evacuation of a hematoma on postoperative day 4, there is improvement in left hepatic artery waveform noted on intraoperative evaluation from a tardus parvus waveform (c) to a normal waveform (not shown). *EDV* end diastolic velocity, *MDV* mean diastolic velocity, *PSV* peak systolic velocity, *RI* resistive index

artery may be ligated or the hepatic artery anastomosis can be made to the enlarged splenic artery [25].

Portal vein complications

Portal vein thrombosis

Portal vein thrombosis is associated with high mortality, particularly in the early postoperative period [26]. Portal vein thrombosis is more common in living donor liver transplants and technical variant grafts due to the smaller size of vessels and shorter vascular pedicles [26]. The reported incidence of early portal vein thrombosis in pediatric patients is between 5.5% and 7.3% [8, 16]. Ueda et al. [26] found that a body weight of less than 6 kg and the use of left-side grafts in pediatric living donor liver transplants were significant risk factors for portal vein thrombosis by multivariate analysis.

On Doppler US, portal vein thrombosis manifests as a filling defect within the portal vein that can be partially or completely occlusive (Figs. 11, 12 and 13). With a completely occlusive thrombus, there is absent color Doppler flow with absent waveform. Of note, acute thrombus can be anechoic; therefore, careful analysis of color Doppler imaging and spectral waveforms is imperative [27]. In the case of a partially occlusive thrombus, Doppler interrogation demonstrates diminished flow, which may be hepatopetal or to-and-fro.

Diminished portal venous flow

We define diminished portal venous flow on sonography as hepatopetal flow less than 10 cm/s, although some authors have used 12 cm/s as a threshold [28]. The differential diagnosis for diminished portal vein flow includes partially occlusive thrombus as described above, external compression, graft rotation, excessive portosystemic collaterals, portal vein stenosis and postoperative edema. External compression is uncommon but can occur in the immediate postoperative period due to large perioperative fluid collections. Graft rotation (Fig. 14) is of particular concern in living donor transplantation, due to the smaller graft size and free movement of the graft, which places the vascular
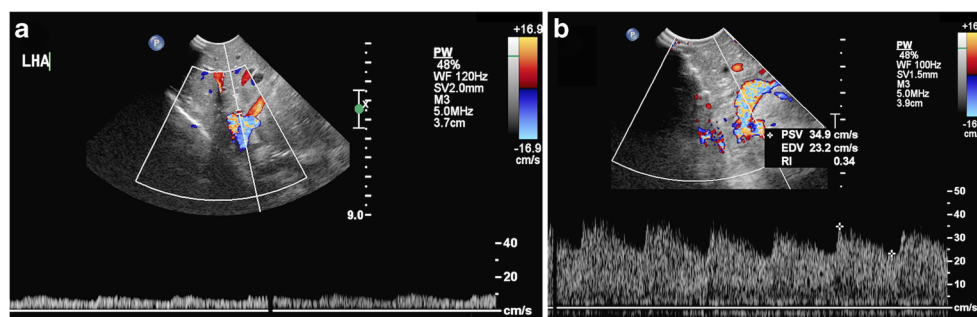

Fig. 10 Splenic artery steal. Intraoperative Doppler interrogation of the left hepatic artery in a 12-year-old girl who received a liver transplant for biliary atresia with marked splenomegaly is shown before (a) and after (b) splenic artery ligation. There is pronounced improvement in the hepatic artery waveform with brisker upstroke and sharper peak after splenic artery ligation. A high diastolic component persists, which resolved by postoperative day 4 (not shown). *EDV* end diastolic velocity, *LHA* left hepatic artery, *PSV* peak systolic velocity, *RI* resistive index
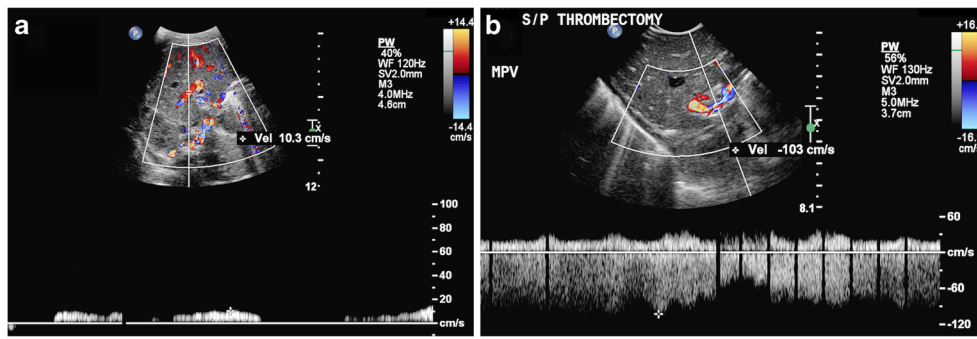
Fig. 11 Portal vein thrombosis. Initial intraoperative Doppler evaluation of the left portal vein (not shown) in a 1-month-old boy who received a liver transplant for fulminant liver failure showed a normal waveform and velocity. On postoperative day 1, Doppler interrogation of the left portal vein shows diminished, intermittent hepatopetal flow within the left portal vein (**a**). Intraoperative Doppler sonogram on postoperative day 1 after thrombectomy of the main portal vein shows improvement in left portal vein flow (**b**), although turbulence is now seen. *MPV* main portal vein, *Vel* velocity
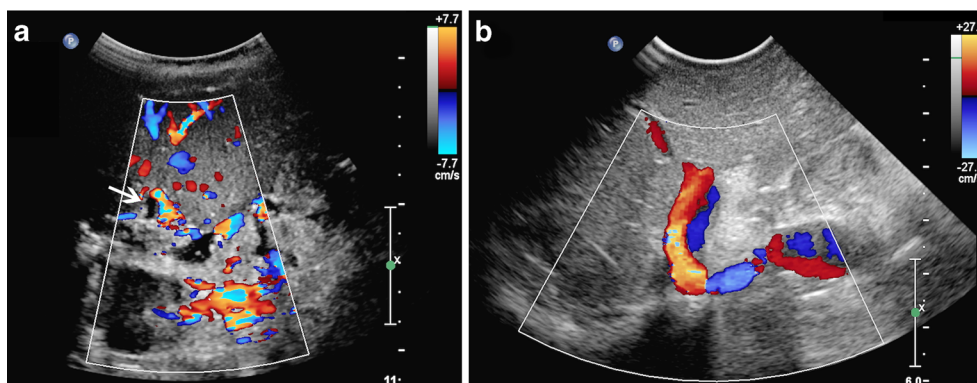

Fig. 12 Portal vein thrombosis and graft placement. Color Doppler evaluation of the main portal vein (**a**) at the bedside on postoperative day 1 in a 9-month-old boy who received a liver transplant for biliary atresia shows an absence of color Doppler flow (*arrow*). Subsequent intraoperative color Doppler evaluation (**b**) after thrombectomy and placement of an interposition graft using donor iliac vein between the recipient superior mesenteric vein and donor portal vein shows restoration of robust portal venous flow. Intraoperative Doppler interrogation of the graft (not shown) confirmed normal directional flow and velocity of the graft

structures at risk for kinking or twisting [11]. Graft rotation may be addressed by various surgical techniques to stabilize the graft. Excessive portosystemic collaterals can be apparent on preoperative imaging and addressed at the time of transplantation [11].

Portal vein stenosis has a reported incidence of 5.6% in pediatric liver transplant patients and is of greater concern later in the postoperative period [28]. Portal vein stenosis typically occurs at the anastomosis, which can be difficult to visualize sonographically depending on the
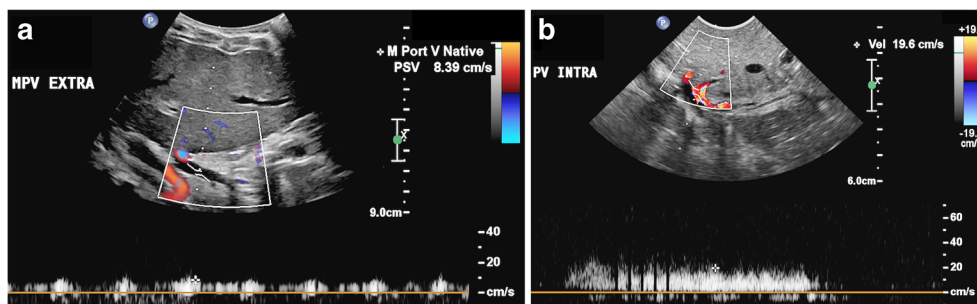

Fig. 13 Portal vein thrombosis and revision. Doppler evaluation of the main portal vein at the bedside (**a**) on postoperative day 1 in an 11-month-old boy who received a liver transplant for familial intrahepatic cholestasis type 2 and hepatoma shows intermittent, low amplitude flow. Intraoperative Doppler interrogation of the intrahepatic main portal vein after thrombectomy and portal vein revision (**b**) shows improved velocity and waveform. *MPV & M Port V* main portal vein, *PSV* peak systolic velocity, *PV* portal vein, *Vel* velocity
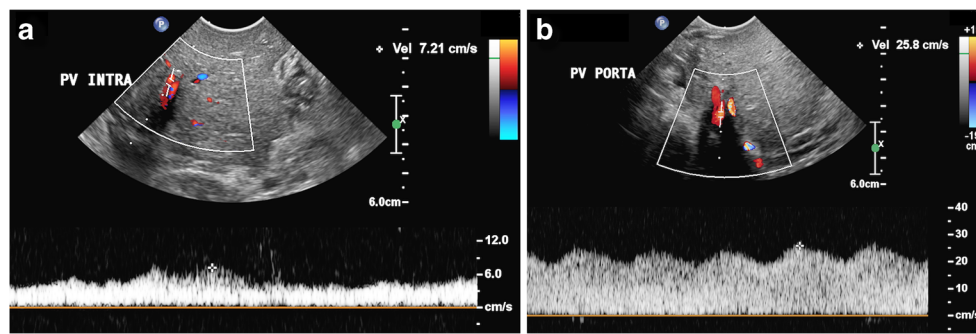
Fig. 14 Portal vein compression from graft rotation. Intraoperative Doppler interrogation of the intrahepatic portion of the portal vein (**a**) prior to delayed abdominal closure on postoperative day 4 in an 11-month-old boy who received a liver transplant for familial intrahepatic cholestasis type 2 and hepatoma shows low amplitude (7 cm/s) antegrade

flow. After repositioning the left lateral segment liver transplant, repeat intraoperative Doppler interrogation (**b**) of the portal vein shows improved velocity (26 cm/s) although mild turbulence is now seen. *PV* portal vein, *Vel* velocity

available acoustic windows. Various US criteria have been studied, including a three- to fourfold increase in velocity at the stenotic site compared to the segment proximal to the stenosis [27, 29]. While portal vein diameters of less than 3.5 mm [29] and 4 mm [28] have been used in the diagnosis of portal vein stenosis, it is important to note that portal

vein diameters vary with age. The portal vein diameter measures approximately 3 mm in neonates, 4–8 mm in healthy 1-year-old patients [29] and up to 11 mm in 12-year-olds [30]. Finally, postoperative edema at the anastomotic site can mimic stenosis in the first ten postoperative days [29].
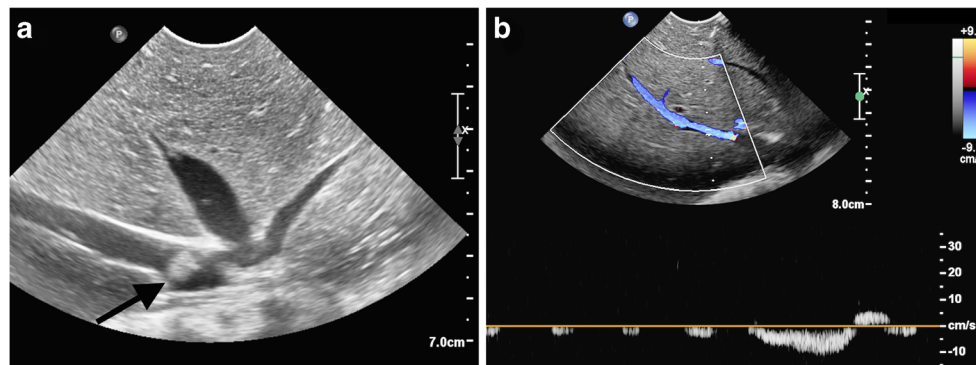

Fig. 15 Hepatic vein thrombosis. Intraoperative gray-scale evaluation of the hepatic vein confluence in a 9-year-old boy who received a liver transplant for metabolic liver disease (**a**) shows an intraluminal echogenic focus (*arrow*) near the confluence of the right and middle veins. On intraoperative color Doppler evaluation, this area showed

trace amounts of flow surrounding the filling defect (not shown), consistent with a nonocclusive thrombus. Intraoperative Doppler evaluation of the right hepatic vein (**b**) shows abnormal low amplitude, intermittent flow with loss of phasicity, corroborating the findings of a nonocclusive thrombus near the venous confluence

Fig. 16 Transplant position-dependent alterations in hepatic venous flow. Intraoperative Doppler evaluation of the hepatic veins in a 9-month-old boy who received a liver transplant for biliary atresia (**a**) demonstrates a monophasic waveform. After repositioning of the left lateral segment graft (**b**), a normal, multiphasic waveform is now interrogated
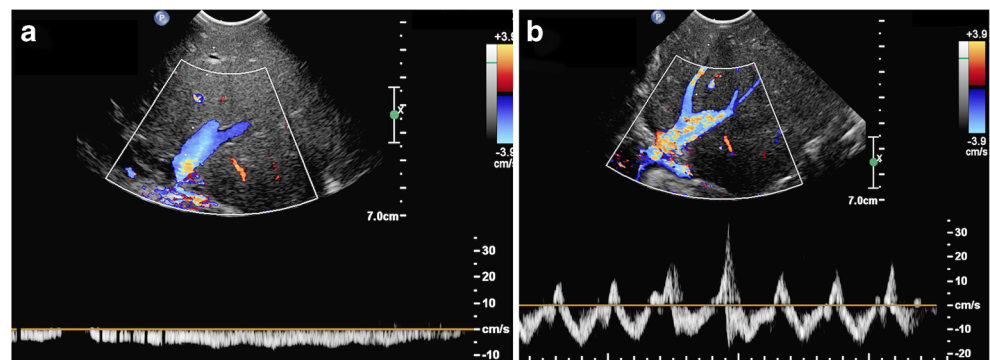
Hepatic vein complications

Hepatic vein outflow obstruction

Hepatic vein outflow obstruction is an uncommon complication with an incidence of between 1% and 6% in pediatric living donor transplantation [31]. Two entities that can cause hepatic vein outflow obstruction are partial or complete hepatic vein thrombosis (Fig. 15) and rotation of the graft causing twisting or compression of the hepatic vein outflow tract (Fig. 16), which is of particular concern in living donor transplantation [31]. Hepatic abscess and biliary-venous fistula may predispose liver transplant patients to hepatic vein thrombosis [32]. With respect to hepatic vein outflow obstruction in the setting of rotation of the graft, left lobe grafts tend to be more susceptible than right lobe grafts, which Shirouzu et al. [33] hypothesized is due to the greater distortion of the middle and left hepatic veins during graft regeneration. In a study of 60 liver transplants, Huang et al. [34] described a pattern of left liver grafts rotating to the right, causing hepatic vein outflow obstruction, in 4 patients.

A monophasic waveform can be seen with hepatic vein outflow obstruction, although this finding is not sufficiently specific for hepatic vein outflow obstruction [35]. The Doppler finding of a fourfold increase in the ratio of the velocity at the anastomosis to the velocity at the hepatic vein trunk 1–2 cm proximal to the anastomosis was 83% sensitive and 76% specific for hepatic vein outflow obstruction [36]. In the absence of positive Doppler findings for hepatic vein outflow obstruction, venography may be necessary to establish a diagnosis, particularly when strongly suspected, such as in patients with otherwise unexplained prolonged ascites [37]. Importantly, the demonstration of a normal, triphasic venous waveform is helpful to exclude hepatic vein outflow obstruction [35].

Conclusion

We have illustrated the normal Doppler findings, common pitfalls, and a spectrum of intraoperative and early postoperative vascular complications in pediatric liver transplant patients. Familiarity with the normal findings, potential complications and their expected time frame of occurrence may facilitate prompt, accurate diagnosis. The use of intraoperative Doppler assessment is particularly useful in identifying vascular complications prior to abdominal closure and, importantly, can be used as a problem-solving tool in situations such as position-dependent kinking of the portal or hepatic veins or in suspected vasospasm of the hepatic artery.

Compliance with ethical standards

Conflicts of interest None

References

1. Ackermann O, Branchereau S, Franchi-Abella S et al (2012) The long-term outcome of hepatic artery thrombosis after liver transplantation in children: role of urgent revascularization. Am J Transplant 12:1496–1503
2. Cheng YF, Huang TL, Chen CL et al (1998) Intraoperative Doppler ultrasound in liver transplantation. Clin Transpl 12:292–299
3. Roberts JP, Hughes L, Goldstone J et al (1990) Examination of vascular anastomoses during liver transplantation by intraoperative Doppler duplex scanning. Clin Transpl 4:206–209
4. Waldman DL, Lee DE, Bronsther O et al (1998) Use of intraoperative ultrasonography during hepatic transplantation. J Ultrasound Med 17:1–6
5. Mun HS, Kim KW, Song GW et al (2010) Evaluation of the hepatic artery anastomosis by intraoperative sonography with high-frequency transducer in right-lobe graft living donor liver transplantation. J Clin Ultrasound 38:10–16
6. Eipel C, Abshagen K, Vollmar B (2010) Regulation of hepatic blood flow: the hepatic arterial buffer response revisited. World J Gastroenterol 16:6046–6057
7. Abdelaziz O, Attia H (2016) Doppler ultrasonography in living donor liver transplantation recipients: intra- and post-operative vascular complications. World J Gastroenterol 22:6145–6172
8. Jamieson LH, Arys B, Low G et al (2014) Doppler ultrasound velocities and resistive indexes immediately after pediatric liver transplantation: normal ranges and predictors of failure. AJR Am J Roentgenol 203:W110–W116
9. Babyn PS (2010) Imaging of the transplant liver. Pediatr Radiol 40:442–446
10. Ren X, Guan J, Gao N et al (2016) Evaluation of pediatric liver transplantation-related artery complications using intra-operative multi-parameter ultrasonography. Med Sci Monit 22:4495–4502
11. Lin TL, Chiang LW, Chen CL et al (2012) Intra-operative management of low portal vein flow in pediatric living donor liver transplantation. Transpl Int 25:586–591
12. Sainz-Barriga M, Reyntjens K, Costa MG et al (2010) Prospective evaluation of intraoperative hemodynamics in liver transplantation with whole, partial and DCD grafts. Am J Transplant 10:1850–1860
13. Caiado AH, Blasbalg R, Marcelino AS et al (2007) Complications of liver transplantation: multimodality imaging approach. Radiographics 27:1401–1417
14. O'Loughlin EV, Stormon MO, Shun A et al (2010) Biliary strictures and hepatic artery flow abnormalities in split liver transplants. Pediatr Transplant 14:121–125
15. Bekker J, Ploem S, de Jong KP (2009) Early hepatic artery thrombosis after liver transplantation: a systematic review of the incidence, outcome and risk factors. Am J Transplant 9:746–757
16. Mali VP, Aw M, Quak SH et al (2012) Vascular complications in pediatric liver transplantation; single-center experience from Singapore. Transplant Proc 44:1373–1378
17. Orlandini M, Feier FH, Jaeger B et al (2014) Frequency of and factors associated with vascular complications after pediatric liver transplantation. J Pediatr 90:169–175
18. Uchida Y, Sakamoto S, Egawa H et al (2009) The impact of meticulous management for hepatic artery thrombosis on long-term outcome after pediatric living donor liver transplantation. Clin Transpl 23:392–399

19. Sanchez SE, Javid PJ, Lao OB et al (2012) Hepatic artery thrombosis and liver malignancy in pediatric liver transplantation. J Pediatr Surg 47:1255–1260

20. Rodriguez-Davalos MI, Arvelakis A, Umman V et al (2014) Segmental grafts in adult and pediatric liver transplantation: improving outcomes by minimizing vascular complications. JAMA Surg 149:63–70

21. Huang TL, Cheng YF, Chen CL et al (2000) Intraoperative Doppler ultrasound in living-related liver transplantation. Transplant Proc 32:2097–2098

22. Garcia-Criado A, Gilabert R, Berzigotti A et al (2009) Doppler ultrasound findings in the hepatic artery shortly after liver transplantation. AJR Am J Roentgenol 193:128–135

23. Uslu N, Aslan H, Tore HG et al (2012) Doppler ultrasonography findings of splenic arterial steal syndrome after liver transplant. Exp Clin Transplant 10:363–367

24. Li C, Kapoor B, Moon E et al (2017) Current understanding and management of splenic steal syndrome after liver transplant: a systematic review. Transplant Rev (Orlando) 31:188–192

25. Dokmak S, Aussilhou B, Belghiti J (2013) Liver transplantation and splenic artery steal syndrome: the diagnosis should be established preoperatively. Liver Transpl 19:667–668

26. Ueda M, Oike F, Kasahara M et al (2008) Portal vein complications in pediatric living donor liver transplantation using left-side grafts. Am J Transplant 8:2097–2105

27. Crossin JD, Muradali D, Wilson SR (2003) US of liver transplants: normal and abnormal. Radiographics 23:1093–1114

28. Huang TL, Chen TY, Tsang LL et al (2012) Hemodynamics of portal venous stenosis before and after treatment in pediatric liver transplantation: evaluation with Doppler ultrasound. Transplant Proc 44:481–483

29. Suzuki L, de Oliveira IR, Widman A et al (2008) Real-time and Doppler US after pediatric segmental liver transplantation : I. Portal vein stenosis. Pediatr Radiol 38:403–408

30. Soyupak S, Gunesli A, Seydaoglu G et al (2010) Portal venous diameter in children: normal limits according to age, weight and height. Eur J Radiol 75:245–247

31. Kawano Y, Mizuta K, Sanada Y et al (2016) Complementary indicators for diagnosis of hepatic vein stenosis after pediatric living-donor liver transplantation. Transplant Proc 48:1156–1161

32. Lee HJ, Kim KW, Mun HS et al (2009) Uncommon causes of hepatic congestion in patients after living donor liver transplantation. AJR Am J Roentgenol 193:772–780

33. Shirouzu Y, Ohya Y, Hayashida S et al (2011) Difficulty in sustaining hepatic outflow in left lobe but not right lobe living donor liver transplantation. Clin Transpl 25:625–632

34. Huang TL, Chen TY, Chen CL et al (2001) Hepatic outflow insults in living-related liver transplantation: by Doppler sonography. Transplant Proc 33:3464–3465

35. Ko EY, Kim TK, Kim PN et al (2003) Hepatic vein stenosis after living donor liver transplantation: evaluation with Doppler US. Radiology 229:806–810

36. Suzuki L, de Oliveira IR, Widman A et al (2008) Real-time and Doppler US after pediatric segmental liver transplantation: II. Hepatic vein stenosis. Pediatr Radiol 38:409–414

37. Sommovilla J, Doyle MM, Vachharajani N et al (2014) Hepatic venous outflow obstruction in pediatric liver transplantation: technical considerations in prevention, diagnosis, and management. Pediatr Transplant 18:497–502