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REVIEW

Expectations from imaging for pre-transplant evaluation of living donor liver transplantation

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Abstract

Living donor liver transplant (LDLT) is a major surgical undertaking. Detailed pre-operative assessment of the vascular and biliary anatomy is crucial for safe and successful harvesting of the graft and transplantation. Computed tomography (CT) and magnetic resonance imaging (MRI) are currently the imaging modalities of choice in pre-operative evaluation. These cross-sectional imaging techniques can reveal the vascular and biliary anatomy, assess the hepatic parenchyma and perform volumetric analysis. Knowledge of the broad indications and contraindications to qualify as a recipient for LDLT is essential for the radiologist reporting scans in a pre-transplant patient. Similarly, awareness of the various anatomical variations and pathological states in the donor is essential for the radiologist to generate a meaningful report of his/her observations. CT and MRI have largely replaced invasive techniques such as catheter angiography, percutaneous cholangiography and endoscopic retrograde cholangiopancreatography. In order to generate a meaningful report based on these pre-operative imaging scans, it is also mandatory for the radiologist to be aware of the surgeon's perspective. We intend to provide a brief overview of the common surgical concepts of LDLT and give a detailed description of the minimum that a radiologist is expected to seek and report in CT and MR scans performed for LDLT related evaluation.

Key words: Liver transplantation; Pre-living donor liver transplant imaging; Vascular anatomy and variants; Biliary anatomy and variants; Computed tomography; Magnetic resonance imaging

Core tip: Living donor liver transplantation (LDLT) has evolved to a widely accepted therapeutic option. As a radiologist, knowledge of the various anatomical variations and pathological states in both the donor and recipient are imperative to generating a meaningful report in pre-operative evaluation. This paper provides a brief overview of the common surgical concepts of LDLT and gives a detailed description of the minimum that a radiologist is expected to seek and report in computed tomography and magnetic resonance scans performed for LDLT related evaluation.

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INTRODUCTION

Living donor liver transplantation (LDLT) has evolved into a widely accepted therapeutic option to ease the persistent shortage of cadaveric livers for deceased donor liver transplantantion (DDLT)[1]. Together with improved surgical techniques and advances in immunology, the

outcome in terms of LDLT recipient survival is as good as those attained after DDLT with full-sized deceased donor organs[2]. LDLT enables healthy volunteers to donate a portion of their liver to compatible recipients. Resection of a portion of the liver from a donor is an immense personal and surgical under-taking; hence a detailed knowledge of the vascular and biliary anatomy and the presence of variants are imperative to ensure safe and successful harvesting of the graft and transplantation[3]. The risk to the donor from LDLT is estimated to be 0.5% mortality and up to 21% post-operative morbidity[4].

In the past, semi-invasive techniques such as catheter angiography and endoscopic retrograde cholangiopancreatography were used to delineate vascular and biliary anatomy respectively. Liver biopsies were commonly performed for ruling out diffuse parenchymal changes such as steatosis. With the exponential progress in computed tomography (CT) and MR techniques, today it is possible to obtain the same information non-invasively. Some of the major limitations of conventional invasive techniques such as morbidity and mortality, high cost, higher radiation exposure as well as sub-optimal demonstration of venous anatomy have been overcome by shifting to pre-operative evaluation with CT and MRI[5].

INDICATIONS FOR TRANSPLANT

The major indications for liver transplantation (LT) are irreversible hepatic failure and hepatocellular carcinoma (HCC)[6]. Advanced cirrhosis secondary to chronic viral hepatitis or alcohol abuse is the most frequent cause of hepatic failure that leads to transplantation[1]. Cholestatic and metabolic diseases are the other pathologies that often result in end-stage liver disease. The usual cholestatic diseases that end up in LT are primary biliary cirrhosis, primary sclerosing cholangitis and biliary atresia[1]. Several metabolic diseases like non-alcoholic steatohepatitis, Wilson's disease, haemachromatosis, cystic fibrosis and glycogen storage disease may eventually need a LT for patient survival[1,7].

RECIPIENT CRITERIA

Various criteria have been described to assess the eligibility of a recipient to obtain a liver transplant. The rationale of these criteria is to ensure that LT is done for those patients who need it the most and in those who are most likely to benefit from it. The guidelines on ensuring fair allocation of the cadaveric graft, a scarce resource, among transplant candidates, have gone through various stages of evolution. Features of decompensated cirrhosis such as ascites, encephalopathy, refractory variceal hemorrhage and hepatorenal syndrome are accounted for while triaging a patient for transplantation[6]. Before 2002, Child-Turcotte-Pugh (CTP) Score was the primary basis for prioritization of candidates for LT. Currently, priority is assigned to a patient on the transplantation list on the basis of his/her highest estimated short-term mortality risk determined using the Model for End-Stage Liver Disease (MELD) score[6]. The MELD is a multiparameteric mathematical score that utilizes the patient's serum bilirubin, serum creatinine and the international normalized ratio to predict survival with higher scores indicating a sicker patient; hence in more urgent need of LT. The MELD was initially developed to predict death within three months of the procedure in patients who had undergone a transjugular intrahepatic portosystemic shunt. As it was found to be a reliable measure in estimation of short-term mortality risk, it was adopted over CTP for determining and prioritizing recipients of LT[8]. Compared to CTP, MELD is a more objective scoring system that avoids potential inter-observer bias and also takes into account renal dysfunction, a common problem among cirrhotics. Adjustments to MELD scores are made for patients with HCC depending on the stage of the disease.

Although HCC is an indication for LT in the appropriate setting, extensive disease can be a contraindication. In 1998 Mazaferro *et al*[9] reported excellent outcomes after LT in patients with a solitary HCC less than 5 cm in diameter or with up to 3 HCC nodules that were each less than 3 cm in diameter; these tumor characteristics and an absence of involvement of the main and primary branches of the portal vein by tumour formed the Milan criteria. Patients outside these criteria are generally believed to have poor tumor biology with high chances of recurrence and hence less likely to benefit from a liver transplant. Strict adherence to Milan Criteria may however preclude patients with a slightly more advanced HCC who may have acceptable, if not excellent long term outcomes from undergoing a transplant. This was the rationale behind the development of the University of California San Francisco (UCSF) criteria. According to UCSF criteria, patients with a single hepatoma < 6.5 cm in diameter or less than 4 hepatomas, with the largest < 4.5 cm in diameter and the sum of the diameters of all the tumors < 8 cm have a recurrence-free survival rate after LT close to that achieved with the Milan criteria[10]. The Milan and UCSF criteria provide broad guidelines to cadaveric liver allocation in many countries. However, every case still merits individual evaluation in a multidisciplinary meeting before being subjected to surgery.

Some of the absolute contraindications to transplantation include active extra-hepatic malignancy, non-hepatic active or uncontrolled infection, thrombosis of the entire portal and superior mesenteric venous system, active substance abuse, advanced cardiopulmonary disease or other co-morbidities that would compromise post-surgical recovery[6].

DONOR CRITERIA

The initial steps in the assessment of a potential liver donor include blood type compatibility, biochemical tests, viral markers and relevant co-morbidities. If these are satisfactory, radiological evaluation follows. If indicated,

a liver biopsy may have to be performed[11]. Variation in anatomy of potential donors can alter surgical approach or even preclude surgery[12,13]. Adequate liver volume with respect to both the graft for the recipient and remnant liver for the donor also needs to be assessed.

SURGICAL CONSIDERATIONS

For the reporting radiologist, understanding the surgeon's perspective on LDLT is imperative so that the necessary information can be conveyed pre-operatively. The three most often harvested grafts for LDLT are the right lobe, left lobe and left lateral segment grafts. The type of hepatectomy is based on the vascular and biliary anatomy as well as the estimated graft and remnant liver volume[14].

Traditionally, liver surgery relies on Couinaud's liver segment classification that divides the liver into eight functionally independent segments[15]. The right hepatic vein (RHV) divides the right lobe into anterior (V and Ⅷ) and posterior (Ⅵ and Ⅶ) sectors, the middle hepatic vein (MHV) divides the liver into right (V-Ⅷ) and left lobes (Ⅱ to Ⅳ) and the left hepatic vein (LHV) divides the left lobe into a medial (Ⅳa and Ⅳb) and lateral part (Ⅱ and Ⅲ). The portal vein divides the liver into superior (Ⅶ, Ⅷ, Ⅳa and Ⅱ) and inferior (Ⅵ, Ⅴ, Ⅳb and Ⅲ) segments.

Left lateral hepatectomy that harvests segment Ⅱ and Ⅲ is the most common LDLT technique and usually used for paediatric recipients or recipients of small size. Most of the adult recipients need a left or right liver graft; this decision depends on the residual volume of donor liver and size of the recipient. The techniques of right or left hepatectomy are fairly standardized worldwide[16-18]. Some controversy exists regarding the inclusion of the middle hepatic vein (MHV) with right or left sided grafts. When the donor's left lobe volume is more than 30% of total hepatic volume, a right hepatectomy (segments V-Ⅷ) can be done[19]. Left lobe is usually small; hence left hepatectomy generally includes the middle hepatic vein so as to obtain a reasonably large graft volume and to maintain good tissue viability for transplantation. However, if the middle hepatic vein is the dominant vein with a small right hepatic vein, this may not be advisable. Right hepatic grafts are often harvested without the MHV trunk. Such grafts are at risk for congestion of right paramedian sector with subsequent graft dysfunction and septic complications. To avoid such outcomes, MHV drainage to recipient IVC may be reconstructed with vascular grafts for segment V and Ⅷ veins[19]. The caudate lobe is generally left behind because of its direct venous drainage in to the IVC. However, for smaller left sided grafts the caudate lobe may need to be harvested together with rest of the left lobe and separate venous drainage reconstruction for the caudate lobe may be required.

IMAGING OVERVIEW

In the past, B mode ultrasound (US) in conjunction with Doppler and color flow imaging formed a routine part of preoperative evaluation of LDLT. However, it is highly operator dependent and subject to factors which are difficult to control and affect image quality such as a large body habitus, a high-riding liver and overlying bowel gas. A key limitation lies in the fact that US has limited ability to estimate liver volume[20]. In current practice, CT and MRI have largely displaced ultrasound from preoperative assessment for LDLT candidates.

In general, the spatial resolution of CT is superior to that of MR. CT is also relatively less expensive, requires a shorter scan time and is more easily assessable. However, CT involves exposure to ionizing radiation. MR on the other hand requires a longer scan time and high degree of patient compliance (*e.g.*, during breath hold sequences). Often normal patients (as these donors always are) do not comply well with these requirements leading to image degradation. Similarly, patients with pacemakers, metallic hardware or claustrophobia may not be able to undergo MR imaging. There is no ionizing radiation involved in MR imaging and it has better contrast resolution than CT scan. In addition, the Gadolinium-based contrast agents used for MR imaging are generally safer compared to the iodinated CT contrast agents with no nephrotoxicity and extremely rare anaphylactic reactions[21].

Source images from both modalities can be post processed for multi-planar reformation and three-dimensional (3D) reconstruction with maximum intensity projection (MIP) and volume rendering (VR) at commercially available workstations. This enables the branching points of the vessels and biliary ducts in relation to their intended site of incision to be viewed with little or no interruption between consecutive sections or on 3D images. 3D imaging with VR gives a stereoscopic view of the anatomy while MIP images may accentuate the visualization of smaller segmental vessels or ducts[22].

In the following sections of this article we will describe the role of CT and MR imaging in the evaluation of the vascular and biliary anatomy along with their variants as well as assessment of the hepatic parenchyma and volumetric analysis. We shall then address the impact of these factors in the selection of potential donors and the surgical decision-making. In our practice, multidetector CT and MRI are used as a compliment to each other in pre-LDLT donor evaluation. Initially the donor undergoes a CT scan that primarily evaluates the vascular anatomy and looks for any gross parenchymal abnormalities; if there is no contra-indication for donor selection on CT scan, further evaluation with MRI is performed for assessing the biliary anatomy and hepatic fat content.

HEPATIC ARTERIAL SYSTEM

According to Couinaud[23], the liver develops in 3 sectors with each one having its own embryological artery; the left gastric artery irrigates the left lateral segment, the common hepatic artery supplies the paramedian segments, and the superior mesenteric artery feeds the right

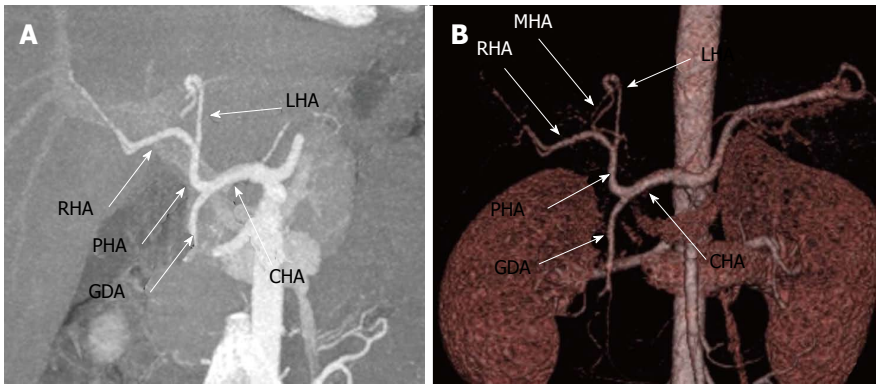

Figure 1 Conventional hepatic arterial anatomy depicted in (A) maximum intensity projection and (B) 3D volume-rendered images generated from a computed tomography angiogram. The CHA comes off the celiac axis, gives off the GDA to become the PHA which then bifurcates into the RHA and LHA. Note the MHA (the slender branch arising from left hepatic artery as seen in 1B) arising from LHA. CHA: Common hepatic artery; GDA: Gastroduodenal artery; PHA: Proper hepatic artery; RHA: Right hepatic artery; LHA: Left hepatic artery; MHA: Middle hepatic artery.

Table 1 Michel's classification of hepatic arterial variants

Type	Frequency of occurrence (%)	Description
I	55	RHA and LHA from the CHA
II	10	Replaced LHA from LGA
III	11	Replaced RHA from SMA
IV	1	Replaced RHA and LHA
V	8	Accessory LHA from LGA
VI	7	Accessory RHA from SMA
VII	1	Accessory RHA and LHA
VIII	4	Accessory RHA and LHA and replaced LHA or RHA
IX	4.5	CHA from SMA
X	0.5	CHA from LGA

RHA: Right hepatic artery; LHA: Left hepatic artery; CHA: Common hepatic artery; LGA: Left gastric artery; SMA: Superior mesenteric artery.

lateral segment. In early fetal life, the liver is large and gut is small; but as the fetus grows, the liver stays relatively small while the gut grows rapidly. The three hepatic arteries fuse at the hilum of the liver, and some of them regress while the enteric branches expand. Thus emerges the conventional hepatic arterial anatomy where the liver is supplied by right and left hepatic arteries after bifurcation of a proper hepatic artery, a branch of the common hepatic artery (CHA) beyond the origin of gastro duodenal artery (Figure 1). This pattern is seen in slightly more than 50% of individuals with many other possible variations[5]. If some of the embryonic hepatic arteries do not regress or fail to detach from their embryonic source, it may result in "aberrant" (variant) hepatic arteries. An aberrant hepatic artery is an artery supplying the liver but arising from a source outside the conventional anatomy (*i.e.,* proper hepatic artery located in the celiac circulation). An aberrant hepatic artery may be "replacing" or "accessory". An aberrant replacing hepatic artery substitutes the normal (usual) hepatic artery that is absent. An aberrant accessory hepatic artery is present in addition to one that is normally (usually) present. Some sort of aberrant (variable) hepatic artery, either replacing or accessory, occurs in approximately 42% of individuals. The Michel classification of hepatic arterial anatomy describes ten subtypes with the variants II, III, V and IX being the most significant ones with respect to LDLT. Table 1 describes the different subtypes and their frequency of occurrence[24].

Both arterial-phase CT and MRI have a diagnostic accuracy comparable to that of catheter angiography and intra-operative finding[13,25,26]. However, Schroeder *et al*[4] found CT to be more accurate in detecting variations in vascular anatomy. This is probably related to the inherently superior spatial resolution of CT compared to MR. Hepatic artery thrombosis (HAT) is one of the most dreaded complications of LT and can be drastically decreased by excluding grafts with unfavorable anatomy[27]. In the past, a potential graft with a narrow hepatic artery of less than 2 mm in diameter was regarded as a contraindication for LDLT due to the high risk of HAT. However, with developments in microvascular surgical techniques, this rarely disqualifies a potential donor from providing the graft[28]. Grafts with multiple arteries and several arterial variants are often not preferred by the surgeon. Grafts with multiple arterial feeders are often found to perfuse poorly in the recipient and may need an alternative inflow source such as an aorto-hepatic interposition graft[29]. A short right hepatic artery is another variant that may often make the anastomosis technically difficult and need extensive reconstructive surgery.

In right lobe grafts, it is important to determine the origin of the segment IV artery[30]. There is some inconsistency in the nomenclature and origin of this artery; it has been variably described as middle hepatic artery (MHA), medial segment artery, left medial artery, and segment IV artery. Anatomical studies suggest that MHA most often arise from the left hepatic artery (LHA) (approximately 60%) while CT based studies show 62.5% of the arterial supply to segment 4 originating from the right hepatic artery (RHA[31]. While harvesting a right-sided graft, it is mandatory to preserve MHA to ensure adequate regeneration and function of the residual liver in the donor. Prior knowledge of MHA variation is especially important since its origin is very difficult to identify intra-operatively unless extensive dissection is done around the porta hepatis. During right lobectomy, the surgeon transects the right hepatic artery, distal to the branches to segment IV and hence it is also prudent to seek the length of the RHA beyond the origin of the segment IV artery so as to ensure there is adequate length of graft hepatic artery to anastomose with the recipient

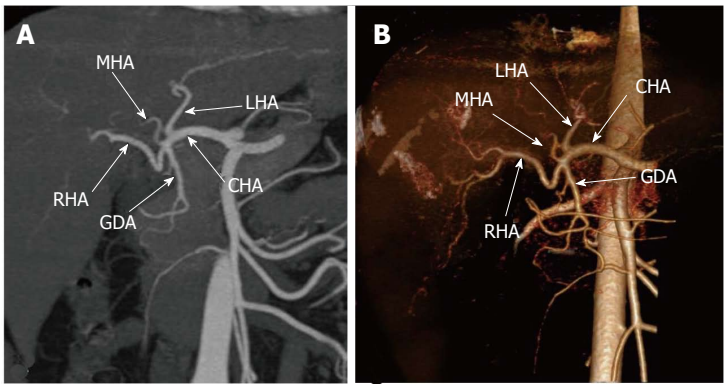

Figure 2 Maximum intensity projection (A) and volume rendered (B) images generated from a computed tomography angiogram shows a variant arterial anatomy. The CHA arises from the celiac trunk, it gives off the LHA followed by the GDA and MHA; thereafter it continues as the RHA in (A) MIP and (B) volume rendered images generated from a CT angiogram. CHA: Common hepatic artery; LHA: Left hepatic artery; GDA: Gastroduodenal artery; RHA: Right hepatic artery; MHA: Middle hepatic artery.

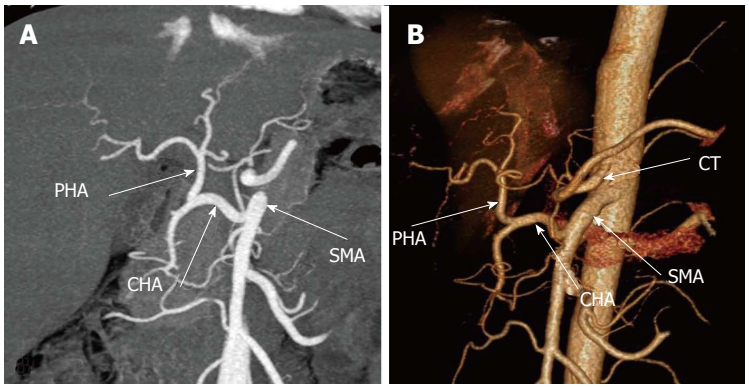

Figure 3 Michel type IX variant is shown in the (A) maximum intensity projection and (B) volume rendered images generated from a computed tomography angiogram. There is a replaced CHA that comes off the SMA. CHA: Common hepatic artery; SMA: Superior mesenteric artery; PHA: Proper hepatic artery; CT-celiac trunk).

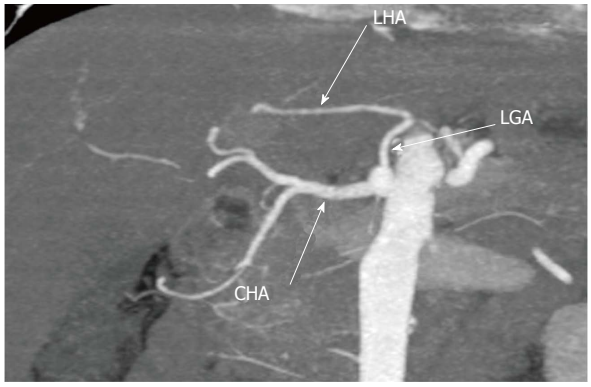

Figure 4 Coronal maximum intensity projection generated from a computed tomography angiogram shows Michel type II variant with a replaced left hepatic artery coming off the left gastric artery. LHA: Left hepatic artery; LGA: Left gastric artery; CHA: Common hepatic artery.

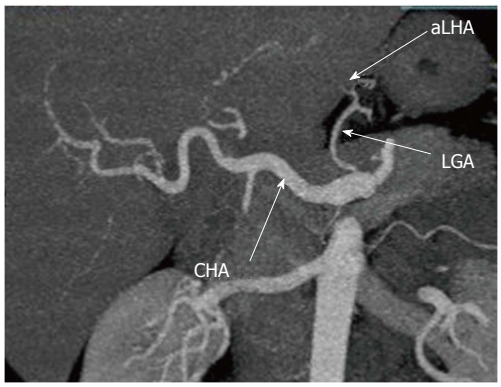

Figure 5 Coronal maximum intensity projection generated from a computed tomography angiogram shows Michel type V variant where an accessory left hepatic artery arises from the left gastric artery. LHA: Left haptic artery; LGA: Left gastric artery; aLHA: Accessory left hepatic artery.

hepatic artery. In left lobe resection, MHA arising from RHA will necessitate two anastomoses: one for the LHA and another one for the MHA.

When the RHA or LHA take off before the origin of the gastroduodenal artery (Figure 2) or if there is a trifurcation of the CHA into the gastroduodenal, RHA and LHA, clamping of the CHA can compromise perfusion to the stomach and duodenum. Such an anomaly can even preclude the subject from being a donor[5]. The main hepatic artery may take an aberrant course deep to the portal vein if it arises from the superior mesenteric artery instead of the celiac trunk (Michel type IX, Figure 3). This variation, when present in the recipient often mandates a change in the usual sequence of vascular anastomoses, such that the portal venous anastomosis will have to follow (rather than precede) the arterial anastomosis[29]. A similar significant variation to be sought in the recipient is a replaced or accessory LHA arising from the left gastric artery (Michel type Ⅱ and Ⅴ, Figure 4 and 5 respectively); this artery would require to be ligated at its origin while removing the native liver to avoid major bleeding. A replaced right hepatic artery arising from the SMA (Michel type Ⅲ, Figure 6) is a significant variation when present in the donor or the recipient as it means additional steps are required for both harvesting and reimplanting the graft[5].

Left lateral segment and left lobe grafts are associated with a higher incidence of arterial complications[32].

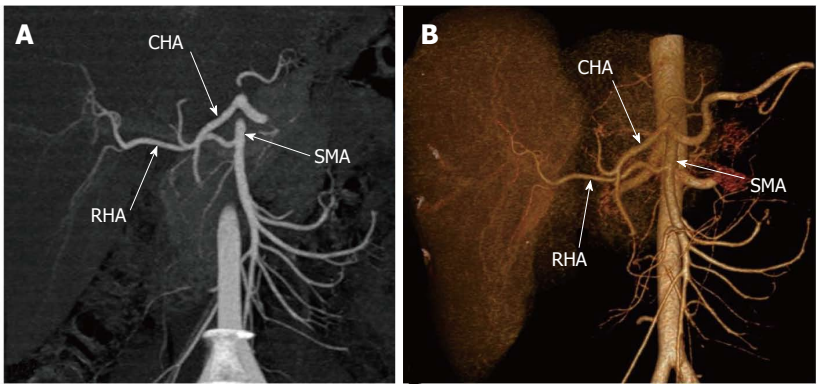

Figure 6 Maximum intensity projection (A) and volume rendered (B) images generated from a computed tomography angiogram shows Michel type III variant with a replaced right hepatic artery arising from the superior mesenteric artery. RHA: Right hepatic artery; SMA: Superior mesenteric artery; CHA: Common hepatic artery.

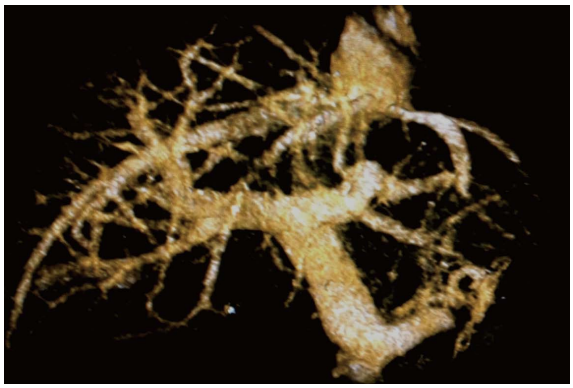

Figure 7 Normal portal and hepatic venous anatomy is demonstrated in this 3D volume rendered image. The MPV divides into RPV and LPV. The RPV then divides into the RAPV and RPPV. The three hepatic veins open into the IVC. MPV: Main portal vein; LPV: Left portal vein; RPV: Right portal vein; RAPV: Right anterior portal vein; RPPV: Right posterior portal vein.

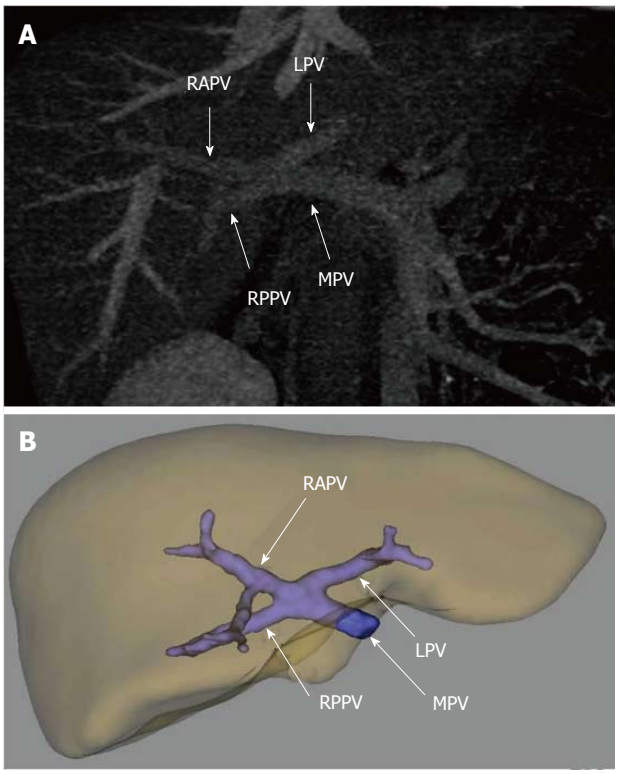

Figure 8 (A) Maximum intensity projection and (B) 3 D volume rendered image generated using dedicated software demonstrates trifurcation of the main portal vein into the right anterior portal vein, right posterior portal vein and left portal vein. MPV: Main portal vein; RAPV: Right anterior portal vein; RPPV: Right posterior portal vein; LPV: Left portal vein.

Complications such as HAT that results in hepatic infarction and bile duct ischemia are more frequent with such grafts[32]. Anastomotic bleeding, stenosis and pseudoaneurysm formation are some of the other common arterial complications. Significant difference in caliber between donor and recipient arteries, small caliber of the anastomosed vessels, clamp injury and presence of an interpositional conduit are among the usual causes for anastomotic stenosis and HAT[33].

PORTAL VENOUS SYSTEM

The normal portal venous anatomy (Figure 7) consists of the main portal vein and its two branching vessels, the right and left portal veins[34]. The right portal vein is a short trunk that further divides into anterior and posterior branches. The left portal vein has a horizontal segment that turns at right angles at the base of the umbilical fissure to form the umbilical segment. The umbilical segment then gives branches to segments II to IV while the caudate lobe receives direct supply from the transverse segment.

The portal venous anatomy is best appreciated in the coronal images[5]. Portal venous variants account for approximately 20% of all significant vascular variants[34]. Up to 20% of potential donors may get excluded from surgery due to variations in portal vein anatomy[35]. The angle of portal vein branching is significant to the recipient. If the angle is too acute, the graft may surround and consume the vein during the regeneration process leading to ischemia and infarction[5]. In such cases, vascular reconstruction may have to be performed. Adequate length of the portal vein is also important for satisfactory anastomosis. A significant portal venous variant to note in a right lobe graft is the presence of portal venules to segment IV as they are important collateral pathways. This knowledge is important for anastomosis and to avoid bleeding and ischemia.

A vital variation is the absence of the right portal vein that is seen in 16.5% of right anterior, right poste-

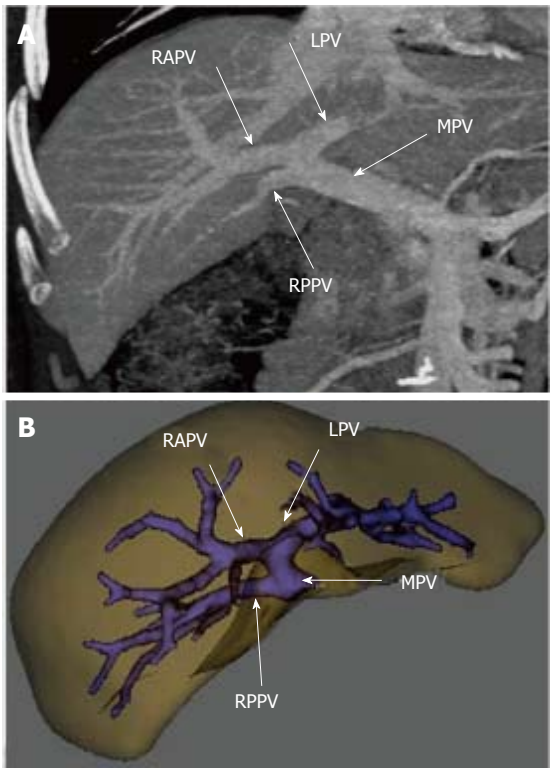

Figure 9 (A) maximum intensity projection and (B) 3 D volume rendered image generated using dedicated software shows an early origin of right posterior portal vein from the main portal vein that later bifurcates in to the right anterior portal vein and left portal vein. RPPV: Right posterior portal vein; MPV: Main portal vein; RAPV: Right anterior portal vein; LPV: Left portal vein.

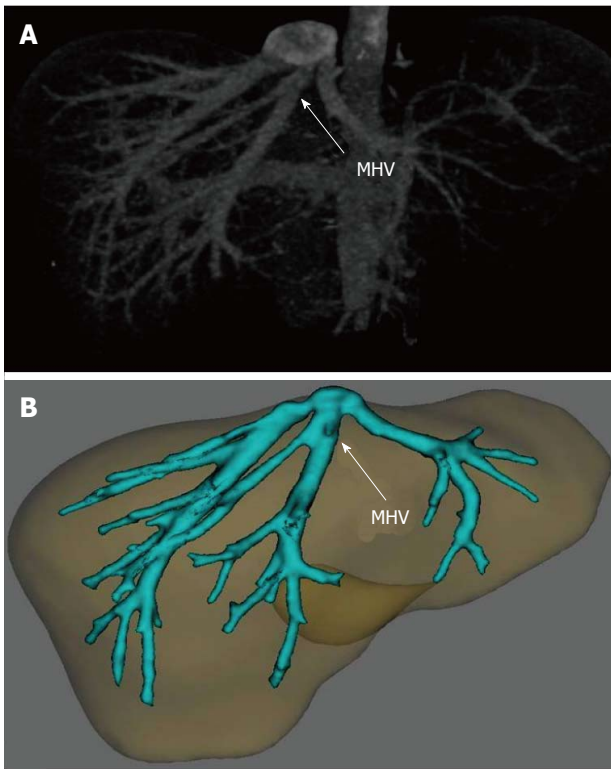

Figure 10 (A) maximum intensity projection and (B) 3 D volume rendered image generated using dedicated software demonstrates early bifurcation of the middle hepatic vein with large veins draining into it from the right hepatic lobe. MHV: Middle hepatic vein.

rior and left portal venous branches (Figure 8) or direct origin of the right posterior portal vein (RPPV) from the main portal vein (Figure 9) or a right anterior portal vein (RAPV) arising from the left portal vein[36]. Trifurcation of the portal vein is important to note pre-operatively as it can often be a contra-indication for surgery or may need alternate surgical planning. For instance, in a right lobe graft, this variant as well as a direct origin of RPPV would necessitate anastomosis of two portal veins, which increases the risk of post-operative portal vein thrombosis[35]. If the RAPV is arising from the left portal vein, the distance of its origin from the bifurcation should be noted. Such donors need the portal vein to be transected distal to the RAPV. Hence there is a possibility that this plane of transection may be intraparenchymal leading to an extra-parenchymal length insufficient for anastomosis to the recipient's portal vein. A left portal vein arising from the RAPV may cause a technical problem during right lobe transplant due to the short length of the graft portal vein.

Diameter of the portal vein is also important and should be measured at the level of the expected anastomosis. The presence or absence of portal vein thrombosis in the recipient can also impact the suitability for a transplant[37]. Acute thrombus may be recanalized by intra-operative thrombectomy. However in case of chronic thrombosis or cavernoma formation, careful scrutiny is required to identify a suitable vein for anastomosis.

Both CT and MR are equally good in providing anatomical information on the portal venous system[4]. Complications that may occur with respect to the portal veins in the recipient are stenosis and thrombosis. Portal vein stenosis tends to develop at the anastomosis while thrombosis is seen with vessel malalignment, differences in caliber of the anastomosed vessels causing turbulent flow or prior thrombosis in the recipient[33].

HEPATIC VENOUS SYSTEM

The plane of transection is determined by the anatomy of the hepatic veins. Hence a detailed hepatic venous mapping that includes the number, size and drainage pattern of the hepatic veins is imperative in CT/MR evaluation of the donor. The normal hepatic venous system comprises of three main venous tributaries that drain into the inferior vena cava (IVC) (Figure 7). Usually, the right hepatic vein (RHV) drains liver segments V-Ⅶ, the MHV drains segments Ⅳ, V and Ⅷ and the LHV drains segments Ⅱ and Ⅲ[38]. Variations in hepatic venous anatomy have been reported in up to 30% of patients[35]. The site of drainage of the middle hepatic vein is particularly relevant. In 60% of cases, the MHV and LHV form a common trunk that drains into the IVC[38].

In right lobe dissection, the surgical plane typically courses 1 cm to the right of the MHV[12]. Early bifurca-

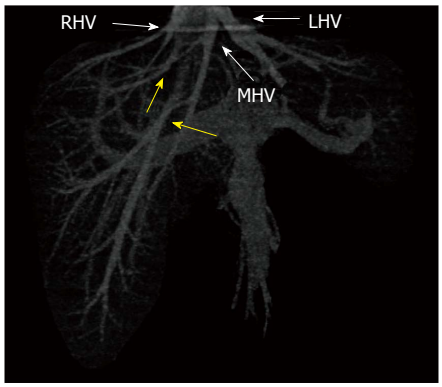

Figure 11 Three-dimensional volume rendered image generated from venous phase computed tomography scan show a relatively small right hepatic vein draining only the dome of the right lobe and two accessory right hepatic veins (yellow arrows). In this case, the caudal accessory right hepatic vein drains the bulk of the right lobe. RHV: Right hepatic vein; MHV: Middle hepatic vein; LHV: Left hepatic vein.

tion of the MHV and large branching veins draining into it from the right lobe (Figure 10) will necessitate alteration of the transection plane as well as separate anastomosis of segment V and Ⅷ branches to the IVC using conduits. Early confluence of the hepatic veins may also result in a small graft that may not be adequate to maintain the metabolic function in the recipient[5,35]. In case of left lobe grafts, the anatomy of segment Ⅳ venous drainage is particularly important. If the segment Ⅳ vein is not patent, the graft would get congested with hepatofugal portal venous flow and eventual graft atrophy. The draining veins of segment Ⅳ can be highly variable, multiple in number and small in caliber often draining into the middle hepatic vein.

In LDLT, special attention must be paid to the presence of accessory hepatic veins draining directly into the IVC that have to be dissected separately and can be a source of excessive haemorrhage if not identified preoperatively[5]. An accessory RHV occurs in 52.5% of patients, two accessory veins in 12% (Figure 11) and an accessory vein draining the caudate lobe in 12% with the most common being the accessory inferior RHV[39,40]. The size of the accessory hepatic vein and its distance from the confluence of the hepatic veins into the IVC should be reported. If this distance is more than 4 cm, it may be difficult to surgically implant both veins in the recipient with a single partially occluded clamp on the IVC[5]. Small accessory veins, usually less than 3 mm in size may be suitable for ligation while a similar treatment of the larger ones can lead to congestion of the graft.

The hepatic veins are best evaluated in the axial plane with the MHV as the landmark. In case of multiple hepatic veins, the vein that extends from hepatic venous confluence with the IVC towards the gall bladder fossa is considered the MHV. CT and MRI are equally good in venous mapping[4]. However, the authors feel most confident about this interpretation when reading non-contrast T1W images. Complications that may occur with respect to the hepatic veins are stenosis and thrombosis,

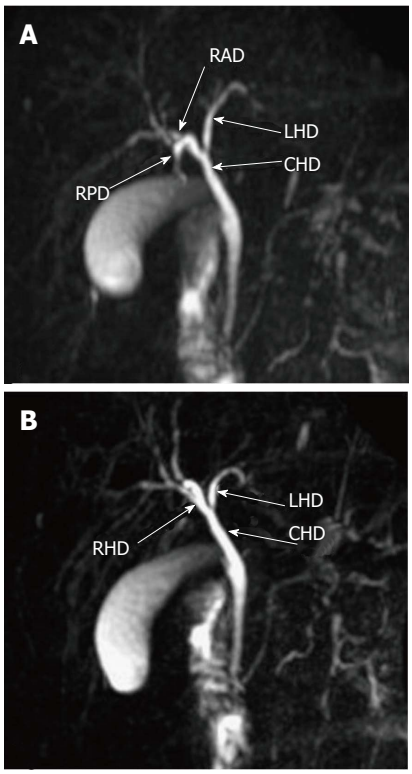

Figure 12 Thick slab magnetic resonance cholangiopancreatography images in different coronal planes demonstrates the normal biliary anatomy where right hepatic duct is formed by fusion of the right anterior duct and right posterior duct. The RHD then joins the LHD to form the CHD. RHD: Right hepatic duct; RAD: Right anterior duct; RPD: Right posterior duct; LHD: Left hepatic duct; CHD: Common hepatic duct.

usually at the site of anastomosis. Again, size discrepancy between the anastomosed vessels is a predisposing factor. Post transplant regeneration of the graft can compresses short and narrow venous anastomoses leading to graft congestion and dysfunction[41]. Various graft materials have been used to create hepatic venous reconstructions allowing for wide ostium anastomoses that can then withstand compression during regeneration[42].

BILIARY SYSTEM

Conventional biliary tract anatomy (Figure 12) is as follows: The right anterior duct drains segments V and Ⅷ, and the right posterior duct drains segments Ⅵ and Ⅶ. The right hepatic duct is formed by fusion of the anterior duct and the posterior duct. The left hepatic duct drains segments Ⅱ, Ⅲ and Ⅳ. The duct draining the caudate lobe usually joins the origin of the right or left hepatic ducts[43]. The right and left hepatic bile ducts merge to form the common hepatic duct (CHD). The cystic duct drains into the CHD below the confluence of right and left hepatic ducts to form the common bile duct. This normal biliary anatomy is seen in only 58% of individuals[44]. The frequency of variations is very high in biliary anatomy[45]. The more frequently encountered and clinically significant variations of biliary anatomy are (1) right posterior duct draining into the left hepatic

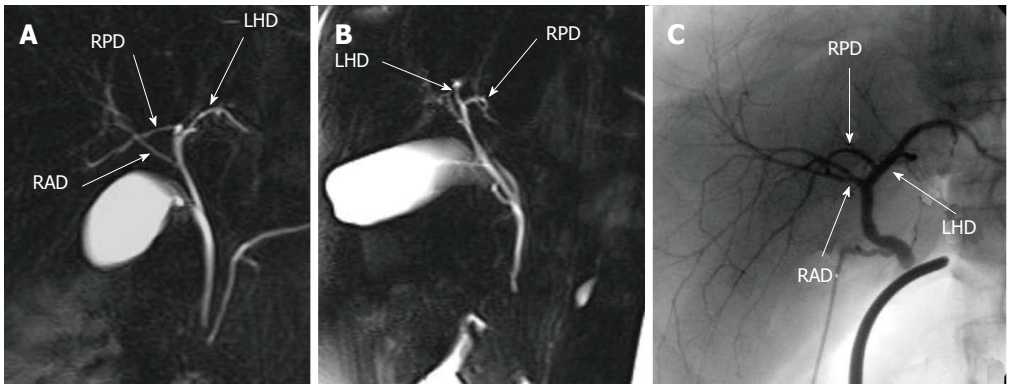

Figure 13 Thick slab coronal magnetic resonance cholangiopancreatography images at 15 degrees left anterior oblique (A) and 80 degrees right anterior oblique (B) projections demonstrate a variant biliary anatomy- the magnetic resonance cholangiopancreatography drains into the magnetic resonance cholangiopancreatography, note the intra-operative cholangiographic appearance of the same variant (C). RHD: Right hepatic duct; RAD: Right anterior duct; RPD: Right posterior duct; LHD: Left hepatic duct; CHD: Common hepatic duct.

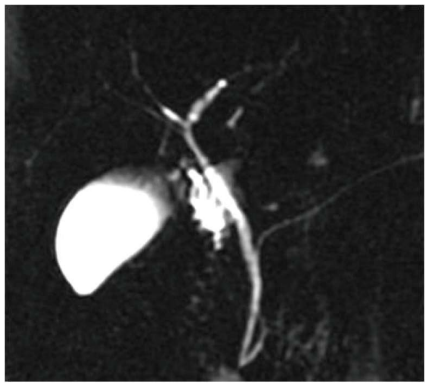

Figure 14 Thick slab magnetic resonance cholangiopancreatography shows a variant biliary anatomy- trifurcation pattern with a common confluence of the right posterior duct right anterior duct and left hepatic duct. RPD: Right posterior duct; RAD: Right anterior duct; LHD: Left hepatic duct.

duct (Figure 13) seen in 13%-19% of individuals[43]; (2) trifurcation pattern where there is confluence of the right posterior, right anterior, and left hepatic ducts (Figure 14) that is seen in 11 % of the population[44]; and (3) the right posterior duct draining directly into the common hepatic duct (Figure 15) or common bile duct. Several other biliary variations involving aberrant and accessory ducts have been described in the literature. An aberrant duct is the only duct draining a particular hepatic segment while an accessory duct is an additional duct draining the same area of liver. Failure to recognize even minor variations can cause post-operative complications like bilomas or biliary leaks that can be extremely difficult to manage.

CT and MR imaging assessment of the biliary tract in potential liver donors include magnetic resonance cholangiopancreatography (MRCP), intravenous administration of liver-specific contrast agents in excretory MR (eMRCP) and CT cholangiogram (CTCh). As the contrast agent used in CTCh is limited to a few countries and not yet available at our institution, MR remains the imaging modality of choice in assessing the biliary tree. The main stay of MRCP in the donor evaluation is a high quality respiratory-triggered thin slice coronal 3D MRCP sequence. In patients with irregular breathing, thin slice 2D MRCP acquisitions in dead coronal as well as right anterior oblique and left anterior oblique projections may be obtained with breath hold. Each of these breath-hold sequences typically takes 15-20 s. Thick slab MRCP in multiple radial planes is optional. We perform eMRCP with gadoxetate disodium (a hepatocyte-specific MR contrast agent) administration followed by three dimensional image acquisitions, 20 min from injection, in all the three orthogonal planes using a 3D fast spoiled gradient echo sequence.

CTCh involves the use of ionizing radiation and the slow infusion of a dilute biliary contrast agent (cholografin). Although acquisition of images is quicker compared to MR, it needs a longer preparation time and there is higher potential for adverse drug reactions with CTCh. The advantages of CTCh include higher spatial resolution (Figure 16) and a lower cost[46]. CTCh allows for depiction to at least the second order intrahepatic biliary ducts. Schroeder *et al*[4] found that MRCP revealed only about one third of the biliary variants found on CTCh. Yeh *et al*[46] also found eMRCP inferior to CTCh in visualization of second order bile ducts. Some studies have shown complete agreement between CTCh and endoscopic retrograde cholangiopancreatography[47,48]. MR imaging of the biliary ducts in general is better suited in the evaluation of pathological states wherein biliary ductal dilatation occurs secondary to obstructing calculi or masses[49] while normal caliber bile ducts of potential donors are better demonstrated with CTCh. The limitations of MR-specific artifacts (*e.g.*, pseudo-obstruction of the common hepatic duct caused by pulsatile vascular compression by the right hepatic artery) do not exist for CTCh[50].

Variations in biliary anatomy have a statistically significant association with variations in portal venous anatomy[51]. Biliary tract complications after liver transplantation have been reported in 10%-25% of cases, proving fatal in up to 10% of complicated cases[52,53]. Biliary complications essentially occur in the form of biliary leaks and anastomotic strictures with the presence of more

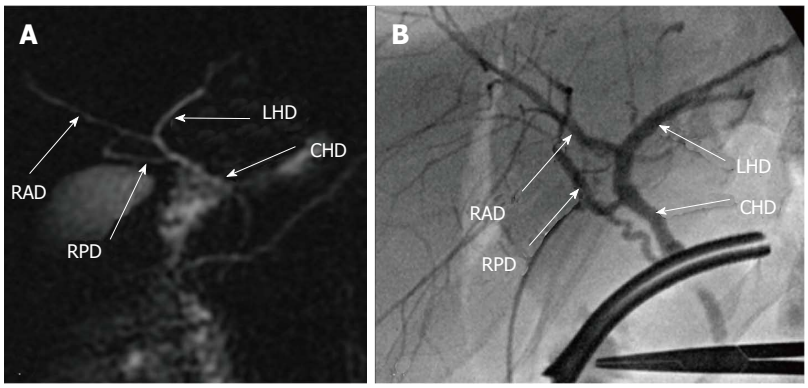

Figure 15 (A) Magnetic resonance cholangiopancreatography and (B) intra-operative cholangiogram in the same patient demonstrates a variant biliary anatomy-the right posterior duct drains directly into the common hepatic duct. RPD: Right posterior duct; RAD: Right anterior duct; LHD: Left hepatic duct; CHD: Common hepatic duct.

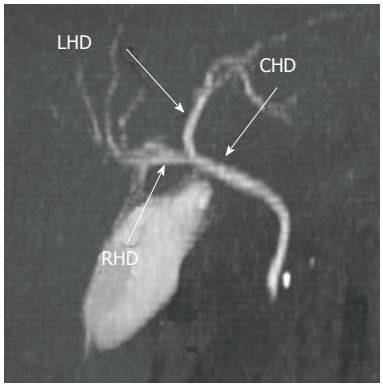

Figure 16 Maximum intensity projection image generated from a computed tomography cholangiogram. Normal biliary anatomy is demonstrated here. LHD: Left hepatic duct; RHD: Right hepatic duct; CHD: Common hepatic duct.

than one graft bile duct and more than one anastomosis increasing the frequency of biliary complications[54]. A bile leak from the cut surface of a graft is typically self-limiting. Biliary strictures may develop at the anastomosis or may occur at non-anastomotic sites secondary to ischaemia caused by hepatic artery compromise[55].

HEPATIC PARENCHYMA

Evaluation of the hepatic parenchyma is mainly to identify and characterize focal liver lesions and exclude diffuse liver disease. Focal lesions have been identified in up to 18% of donor liver evaluations[25]; however most of them are benign cysts or haemangiomas. MR is superior in characterization of focal liver lesions[56,57]. Fatty liver is the most common diffuse liver disease that may preclude an outwardly healthy patient from being a donor. Grafts with more than 30% fatty change carries high risk of graft non-function in the recipient and liver dysfunction in the donor[58]. Hence pre-operative detection and quantification of fatty liver is vital. Uniform fatty change of the liver is easier to quantify; however hepatic steatosis can often be heterogeneous. Generally, fatty changes are more pronounced in the right lobe than in the left as former receives greater amount of portal venous blood flow.

Hepatic steatosis is identified on CT scan as reduced attenuation relative to the spleen (Figure 17). This is best evaluated on a non-contrast study as relative densities of the liver and spleen can vary on post contrast scans depending on the phase of image acquisition[27]. The attenuation value of normal liver on unenhanced CT ranges between 55 and 65 Hounsfield units (HU) and is generally at least 8 HU higher relative to the spleen; the liver is regarded as fatty when the liver attenuation is at least 10 HU less than the spleen[59]. This method has high sensitivity (88%-95%) and specificity (90%-99%)[60]. Liver attenuation values also reflect the severity of fatty change. Hepatic CT attenuation value below 48 HU may be considered as fatty liver and a value of 40 HU represents approximately 30% fatty change[61]. With more than 30% macrovesicular steatosis the hepatic parenchyma appears hypoattenuating compared to the hepatic vessels on non-enhanced CT scan[62]. Similarly, a hepatic to splenic attenuation ratio of 0.8 is almost 100% specific for moderate to severe (> 30%) macrovesicular steatosis[63]. According to Limanond *et al*[64], a hepatic-splenic attenuation difference of more than 5 HU was consistent with absence of significant macrovesicular steatosis (0%-5%), a difference of -10 to 5 HU was suggestive of mild to moderate steatosis (6%-30%). The same authors reported a specificity of 100% for the detection of moderate to severe (> 30%) macrovesicular steatosis when the hepatic-splenic attenuation difference was less than -10 HU. Dual energy CT can also be used in detecting and quantifying hepatic steatosis but there is limited literature to validate its utility in this context.

MR is an extremely sensitive modality in detection and characterization of hepatic steatosis. Fatty liver is seen as increased signal intensity on conventional T1W spin echo sequence. However, these sequences are seldom used for hepatic fat evaluation due to their poor sensitivity. Detection and quantification of fatty liver is much better performed with chemical shift imaging or MR proton spectroscopy[27]. Chemical shift imaging utilizes the differences of resonance frequencies between water and fat

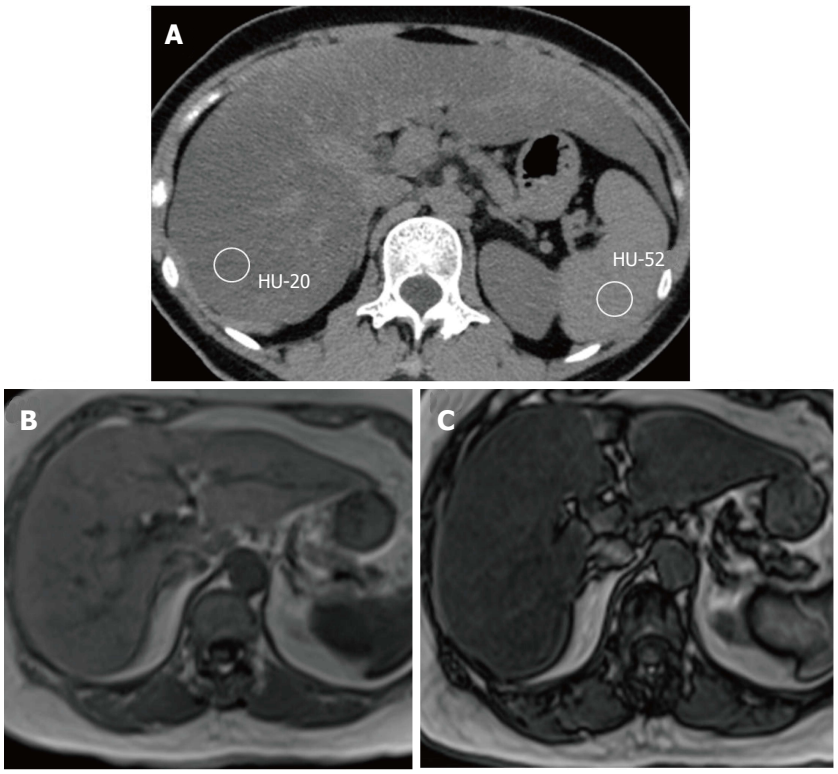

Figure 17 Diffuse hepatic steatosis is demonstrated here. In the non-enhanced computed tomography scan (A) the hepatic parenchyma has significantly lower attenuation than spleen. The out phase magnetic resonance imaging image (C) shows a drop in the hepatic signal intensity compared to that in the in-phase image (B).

proton signals to quantify fat accumulation. By acquiring images at echo times when water and fat signals are in-phase and out-of-phase, the extent of hepatic steatosis can be quantified based on signal change[65]. Loss of signal on out-of-phase images suggests fatty liver (Figure 17). Nowadays, the in-phase and out-of-phase images are obtained near simultaneously (*i.e.,* less than a few milliseconds apart) using breath-hold gradient-echo sequences. The spleen or skeletal muscle can be used as an internal standard for calculating the percentage of relative signal loss of the liver[66]. This technique provides a relatively simple way of estimating the degree of steatosis. Three circular regions of interest (ROI) can be placed in the liver; two in the right lobe and one in the left with three ROI placed within the spleen at anatomically matched levels. The mean signal intensity can then be calculated using the formula: $[(SI_{\text{in-phase}} - SI_{\text{out-of-phase}})/SI_{\text{in-phase}}] \times 100$ where SI = average liver signal intensity/average spleen intensity[67]. Fischer *et al*[68] found that this dual echo MR imaging technique for liver fat quantification was actually superior to histopathological analysis. This method is accurate in detection of hepatic fat fraction when it is in the 15%-50% range. Although this method is technically simple and highly sensitive, absolute quantification of hepatic fat is not possible with this technique. Fast spin echo T2 weighted sequences with and without fat saturation may be used in a similar fashion to estimate fat fraction of the liver.

MR spectroscopy is the most accurate non-invasive method of evaluating fatty liver. It can quantify the absolute fat concentration in the liver and is highly sensitive to small changes in hepatic triglyceride levels.

LIVER VOLUME

The size of the graft is one of the most crucial factors that have to be taken into account when considering LDLT[69]. The normal liver weighs between 2%-2.7% of the total body weight; for LDLT, a graft that is at least 0.8% of the recipient's body weight ratio is considered adequate. Liver remnant volume of 30%-40% of the total liver volume is adequate for donor survival, this is provided the liver parenchyma is normal[70]. The minimum graft volume required to provide sufficient functional hepatocytes to the recipient is about 40% of the standard liver mass[71], which can be calculated using the body surface area[72].

If the graft is too large, haemostasis, vascular anastomosis and abdominal closure may prove problematic[20]. A graft that is too small has increased likelihood of dysfunction secondary to inadequate functional hepatic mass and possible excessive portal perfusion[73]. A small for size graft is also prone to torsion and may necessitate additional surgical maneuvers like fixation of falciform ligament to anterior aspect of the peritoneal cavity[27].

For volumetric analysis, any cross-sectional imaging that provides sufficient contrast between the liver parenchyma and the surrounding tissues can be used. This is achievable both with portal venous phase CT and T1-weighted MR, with CT being marginally superior due to inherently sharper images obtained with it[4]. Hepatic volumes can be determined by manually tracing the contours of the entire liver and the intended graft excluding the large vessels, major fissures and the gallbladder fossa using contiguous CT or MR images[70]. The cross-sectional area within the region of interest is determined on

each slice and the sum of all the slices estimates the liver volume. 3D software reconstruction of the liver can be performed which allows the surgeon to better determine the size and shape of the intended graft by performing virtual hepatectomies. Dedicated software programs also allow calculation of the potential residual volume in the donor and the potential volume in the recipient by clicking a few buttons[74]. Studies have shown that automated volumetric results are comparable to manual volumetric results with the former being more efficient[75,76]. Usually the calculated liver volume over-estimates the weight of the graft[70], this is most likely due to lack of perfusion of the graft when it is weighed intra-operatively.

CONCLUSION

As discussed above, CT and MR are complementary modalities that allow for a comprehensive non-invasive assessment of a potential liver donor while either of these modalities is adequate for pre-transplant radiological assessment of a potential recipient. Knowledge of the broad indications and contraindications to qualify as a recipient for LDLT is essential for the radiologist reporting scans in a pre-transplant patient. Similarly, awareness of the various anatomical variations and pathological states in the donor is essential for the radiologist to generate a meaningful report of his/her observations. A radiologist oblivious to these facts would not be able to effectively harness the immense potential of non invasive imaging modalities in contributing towards a LT program.

Both CT and MR are comparable in terms of illustration of vascular anatomy. MRCP and in particular eMRCP are extensively used for evaluating the biliary anatomy of the potential donor. Few studies have shown CTCh to be superior to MRI for this purpose, but limited availability of the CT cholangiographic contrast agent limits the application of this technique. MR outperforms CT in evaluation of focal liver lesions and diffuse parenchymal disease. Volumetric analysis is marginally better with CT compared to MRI.

In most successful LDLT programs the radiologist is an integral part of the transplant team and is present during transplant planning discussions. Only a cross-fertilization of knowledge in their respective areas can lead to a high level of predictability of transplant results and an ongoing increase in success of the program.

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