Introduction

The advent of multidetector computed tomography (MDCT) scanners has provided an impetus for various changes in applications of computed tomography (CT) principles and their implementation in the design of CT protocols. The advanced MDCT scanners can produce isotropic voxel resolution, which can improve detection of subtle lesions in the organ. It thus remains the major imaging modality for detection of hepatic pathologies [1-4]. The main area of improvisation by MDCT for liver imaging appears to be in detection and characterization of small liver malignancies with better characterization of benign pathologies and vascular flow details [5]. Studies have shown that thinner images with MDCT provides some benefits, such as reduced volume-averaging artifacts, thereby improving diagnosis of focal hepatic lesions and hepatic vascular pathologies [6, 7]. Also, due to shorter hepatic arterial acquisition time and thin collimation with MDCT, multiplanar imaging and CT angiography are much better [8].

Basic Concepts for Liver Imaging

The enhancement pattern of the arterial phase is dependent on the contrast medium injection rate, injection duration, and the time of the scan performed relative to the contrast bolus. The arterial opacification can primarily be controlled by the iodine administration rate, which is further dependent on the flow rate and the concentration of medium administered. It is important that the injection duration be longer than the scanning time to ensure strong vascular enhancement by the recirculation of contrast.

On the other hand, the parenchymal enhancement is independent of the injection flow rate and depends on the total volume (dose) of contrast administered. Thus, to obtain optimal liver parenchymal enhancement, a sufficient volume of contrast medium is required (approximately 120–150 cc of 370 mgl contrast agent). The iodine dose is directly proportional to the contrast volume administered and/or the iodine concentration of the contrast medium. Thus, increasing either would lead to an increase in dose. For example, for vascular mapping of the liver [computed tomographic angiography (CTA)], arterial phase imaging is of paramount importance, and administration of a smaller volume of high-concentration contrast medium at a higher rate would suffice.

Contrast material later enters the extracellular space by diffusion, and this reduces the conspicuity of the liver lesion and its contrast with the surrounding parenchyma, later causing obscuration of the lesion. This is called the equilibrium phase, and it is important that the scan be completed well before this stage sets in.

Dual-Phase Imaging

Normally, the liver derives only 25% of its blood supply from the hepatic arterial flow and the remaining 75% from the portal venous system [9]. After the administration of iodinated contrast medium, opacification of hepatic arteries is encountered first, usually at 15–25 s (arterial phase). Liver enhancement in the portal venous system usually occurs between 45 and 55 s, followed by hepatic venous opacification at 60–70 s after contrast injection (portal venous phase). Based on the contrast circulation, the hepatic arterial phase (HAP) can be further divided into an early (true) arterial phase in which there is opacification of the hepatic arterial system without much parenchymal enhancement and a following late (dominant) arterial phase, which not only permits optimal
opacification of the hepatic arteries but also higher parenchymal enhancement. This information is important in designing MDCT protocols, as hypervascular lesions are best visualized in the late arterial phase. In other words, better hepatic parenchymal contrast in the HAP is produced as a consequence of greater enhancement of hypervascular lesions and relatively less enhancement of the background liver parenchyma (Fig. 1). In the subsequent portal venous phase, these lesions are less conspicuous due to the higher enhancement of background liver parenchyma. Studies have demonstrated that HAP images reveal more numerous benign and malignant hypervascular liver lesions than portal venous phase (PVP) images [10], where most hypovascular lesions are evident (Table 1). Hence, dual-phase CT of the liver is performed in the late HAP and the PVP. Although initial reports supported the use of triple-phase scanning (early and late HAP and PVP) for evolution of hypervascular lesions, subsequent studies revealed no additional benefits of the early phase. Because of this and because of additional concerns relating to excess radiation dose, the early HAP is losing importance (Fig. 2) [11].

Fig. 1a, b. Hepatocellular carcinoma detection: coronal reformatted computed tomographic (CT) images of the liver in the arterial phase (a) showing intensely enhancing hepatocellular carcinoma (HCC) (arrow). Note better lesion-to-parenchymal contrast in the arterial-dominant phase in comparison with the portal venous phase image (b) where the lesion is not appreciated

Table 1. List of common hypervascular and hypovascular lesions encountered in the liver

<table>
<thead>
<tr>
<th>Hypervascular lesions (arterial phase)</th>
<th>Hypovascular (PVP) lesions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malignant</td>
<td>Metastases</td>
</tr>
<tr>
<td>• Primary malignancy</td>
<td>• Lung carcinoma</td>
</tr>
<tr>
<td>• Hepatocellular carcinoma</td>
<td>• Colon carcinoma</td>
</tr>
<tr>
<td>• Melanoma</td>
<td>• Breast carcinoma</td>
</tr>
<tr>
<td>Metastases</td>
<td>Benign</td>
</tr>
<tr>
<td>• Carcinoid</td>
<td>• Cysts</td>
</tr>
<tr>
<td>• Islet cell tumors</td>
<td>• Biliary hamartoma</td>
</tr>
<tr>
<td>• Renal cell carcinoma</td>
<td></td>
</tr>
<tr>
<td>• Melanoma</td>
<td></td>
</tr>
<tr>
<td>Benign</td>
<td></td>
</tr>
<tr>
<td>• Hemangioma</td>
<td></td>
</tr>
<tr>
<td>• Focal nodular hyperplasia</td>
<td></td>
</tr>
<tr>
<td>• Hepatocellular adenoma</td>
<td></td>
</tr>
</tbody>
</table>

PVP portal venous phase
II.1 • Dual-Phase Liver MDCT

Rationale for High-Concentration Contrast Medium

When a CT scan was performed with old scanners (conventional, helical, and dynamic), the liver was predominantly scanned during the preequilibrium phase due to slower scan speed and lengthened bolus time. With the evolution of MDCT, due to the reduction in scanning time, the scans can be performed during optimal phases with near perfection. One way of achieving this is by increasing the injection speed. The other way is to increase the concentration of the iodinated contrast medium.

There should be an optimal balance between iodine concentration in the contrast and the volume of material injected for the desired hepatic parenchymal enhancement. The use of high iodine concentration contrast medium has gained importance in patients with decreased cardiac output, obesity, in conditions such as cirrhosis of the liver or portal vein thrombosis, and other conditions where there is decreased liver perfusion. It has been observed that the maximum hepatic enhancement in obese patients is significantly lower than in those who are lighter in weight. This could be attributed to the decreased level of perfusion of the liver in obese patients [12]. Also, in cases of liver cirrhosis, due to decreased portal perfusion, the peak contrast enhancement in liver is late, and usually, the plateau of contrast enhancement occurs in the late portal phase. This is again secondary to decreased portal perfusion seen in these patients [13]. The injection of contrast medium with standard iodine concentration could increase the possibility of missing hypovascular metastases during the late phase in heavy patients or in patients with cirrhosis or chronic hepatitis.

The use of high concentration contrast medium enables better visualization of the heterogeneous enhancement pattern in cirrhotic patients. The use of high concentration contrast medium for MDCT enables greater enhancement of the aorta in the early and the late arterial phases [14, 15]. It also results in higher mean attenuation of the liver in the portal phase than would be achieved by use of contrast medium of lesser iodine concentration. Therefore, the lesion-to-liver contrast can be improved when high iodine concentration contrast medium is used (Fig. 3).

Other Technical Considerations for Liver Imaging

Appropriate selection of the delay for scan initiation is essential, along with modification of the contrast administration protocol. Various technical and physiological factors affect MDCT contrast enhancement of the liver [16, 17].

Scan Delay and Contrast Delivery

With increasing detector rows in CT scanners, scan delays and contrast delivery in liver protocols need to be altered accordingly. As discussed, if the volume of contrast to be administered is kept constant and the rate is increased, the delay for peak aortic enhancement decreases [16]. Also, in patients with decreased cardiac output or more body weight, a longer time is required for the contrast to demonstrate peak aortic enhancement and thereby liver parenchymal enhancement. Thus, optimal enhancement in larger patients can be achieved by
increasing the injection rate, and the time required for each of the phase acquisitions varies from patient to patient.

**Techniques for Contrast Delivery Optimization**

Timing of the hepatic arterial phase following contrast administration is of vital importance, and with the availability of computer-automated scanning technology (CAST), fixed time delays can be planned. However, fixed time delays do not take into account the patient-to-patient variability in cardiac output or the contrast circulation time.

Almost all recent scanners are now equipped with automated scanning trigger software wherein a threshold enhancement (Hounsfield units (HU)) in a vessel or an organ is preselected to initiate a scan after injection of contrast. A few initial images are obtained at a static table position, and after the contrast bolus arrives and the threshold of enhancement in the region of interest is reached, scans can be initiated either manually or automatically. Alternatively, a test bolus can be used wherein a small amount of contrast (10–15 ml at 3-4 cc/s) is injected and serial images are obtained through the upper aorta to judge its maximal opacification and determine the appropriate delay time for the patient. A test bolus is accurate but does entail additional contrast and time. With both the test bolus and automatic triggering techniques, the scan should be performed at the point of maximal opacification of the hepatic arterial system. This should enable creation of excellent images of the vascular anatomy of the liver.

However, for venous phase imaging, delays of 65–70 s, 60 s or less from the start of injection, are usually planned in 4-slice, 16-slice, and 64-slice scanners, respectively. This ensures optimal opacification of the portal vein and the hepatic veins.

**Contrast Volume**

Reduced volumes of contrast injection are not favored for liver imaging due to concerns about image quality. Unlike thoracic and vascular CT imaging, the authorities still recommend 120–150 ml of contrast medium of concentrations up to 300–370 mg of iodine [18]. However, in larger patients, an increased volume of up to 180 ml has been administered. In particular, patients with cirrhosis require a higher volume of contrast to achieve optimal parenchymal enhancement due to decreased liver perfusion.

Also, the volume of contrast to be injected varies depending on the iodine concentration in the contrast medium. Usually in cases of MDCT liver imaging, 120–150 cc of 300 mg/ml of non-ionic contrast is injected at a rate of 4 cc/s. On the other hand, if 370 mg/ml is used, only 80–100 cc would be required, but this needs to be balanced with a slightly higher injection rate of 4–5 cc/s. Thus, with use of higher or lower iodine concentration contrast media, appropriate adjustments in injection rate and contrast volume are needed.

**Pitch and Scan Collimation**

The use of thinner collimations with increases in detector configuration of CT scanners has revolutionized the role of CT scans in imaging of liver pathologies. It has been shown that the use of 2.5 mm collimation markedly improves the detec-
tion of liver lesions compared with imaging on scanners with higher collimation such as 10 mm, 7.5 mm, and 5 mm [6]. For hepatic parenchymal imaging, 2.5 mm collimation is typically selected with a 4-row MDCT, but with increasing detector rows, such as 16- and 64-slice CT, collimations as thin as 1.25 mm and 0.625 mm can be obtained.

One of the most important factors that determines the pitch is the table speed (Table 2). New-generation MDCT scanners provide better coverage using the maximum table speed, which is due to the presence of their respective detector configurations and more data elements (Table 2). However, it is possible that this may result in unacceptable noise in the images.

Reconstruction Interval

It was shown by Kawata et al. [19] that there is no significant difference in the images obtained by using intervals of 2.5 mm, 5 mm, and 7.5 mm for detection of hypervascular hepatocellular carcinomas. It is essential that overlap of reconstructions be at least 50% to obtain optimal image quality particular for hepatic CT angiography. Although thinner slices are desirable, reconstruction intervals of less than 2 mm can add to the noise in the image and thus affect the rate of detection of liver lesions. However, retrospective reconstruction from thinner collimated images of isotropic voxel resolution promotes reduction of partial-volume artifacts.

Role of MDCT in Imaging of Liver Tumors

The advent of MDCT scanners has ensured the availability of fast data acquisition, thinner collimations, and near-isotropic voxel resolution, but along with this has come alterations in scan delay and rate of contrast administration as well as emphasis on the importance of contrast concentration.

The two most important factors that influence the detection of lesions is lesion size and its intrinsic vascularity. Lesions as small as 1 mm have been detected by MDCT. It is generally believed that a minimum of 10 HU difference between lesion and normal liver parenchyma is required for the lesion to be detected. Different tumors may enhance at different phases of the scans depending on tumor vascularity. It must be noted that most tumors derive their blood supply from the hepatic artery and its branches. However, some may be more vascular than others and thus show increased enhancement on the hepatic arterial phase of the scan. Such tumors are classified as hypervascular tumors. Examples are hepatocellular carcinomas, metastases from melanoma, breast cancer, carcinoid, thyroid medullary carcinoma, islet cell tumors, and renal cell carcinoma.

Certain benign lesions also show increased vascularity in the hepatic arterial phase of the scan, such as focal nodular hyperplasia and hemangiomas less than 1 cm. This advantage of tiny lesion detection by MDCT scanners revealed that benign tumors in conditions such as cysts, focal nodular hyperplasia, hemangiomas, and adenomas occur in up to one third of the population without known malignancy [20]. In addition, MDCT detects tiny lesions, such as metastases in the liver, at an early stage, thereby ensuring early surgery, ablation therapy, or chemotherapy.

As we have moved to the era of 16- and 64-slice CT scanners, a study of the subtle enhancement pattern of tiny hypodense liver lesions in the hepatic arterial phase can be performed [21]. MDCT can detect the peripheral rim enhancement in hypovascular lesions and can very well depict involvement of the adjacent vasculature by the tu-

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**Table 2. Multidetector computed tomography (MDCT) liver protocols on different computed tomography (CT) scanners**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>4 Channel</th>
<th>16 Channel</th>
<th>64 Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC (mm)</td>
<td>4×1.25</td>
<td>16×0.625</td>
<td>64×0.6</td>
</tr>
<tr>
<td>TS (mm/s)</td>
<td>15</td>
<td>18.75</td>
<td>38</td>
</tr>
<tr>
<td>Pitch</td>
<td>1.0–2.0</td>
<td>0.938</td>
<td>0.984</td>
</tr>
<tr>
<td>Slice thickness (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arterial phase (CTA)</td>
<td>1.25</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Arterial phase (liver)</td>
<td>2.5–5.0</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Venous phase (CTA)</td>
<td>2.5</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Venous phase (liver)</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Arterial Delay (s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venous Delay (s)</td>
<td>65–70 s</td>
<td>60 s</td>
<td>50–60 s</td>
</tr>
<tr>
<td>Bolus tracking/automated trigger</td>
<td></td>
<td>Empirical delay: 25–30 s</td>
<td></td>
</tr>
</tbody>
</table>

DC detector collimation, TS table speed, CTA computed tomographic arteriography.
Early detection of small hypervascular metastases and primary tumors by MDCT is important for early treatment planning. Due to the inherent capability of MDCT scanners to outline smaller and more subtle lesions much earlier in the disease process, routine screening for hepatitis B patients is performed to detect early development of neoplasia in the liver. In such patients, the ability of MDCT to pick up tiny lesions in different phases of the scan proves to be a crucial imaging modality. Patients with small tumors of less than 5-cm diameter may be candidates for liver transplantation. Studies have shown the importance of late arterial phase scans for detection of tiny liver tumors [23, 24]. But due to constraints posed by inaccurate bolus tracking methods, which may lead to significant hepatic venous enhancement in the late arterial phase, the use of both phases is justified [25].

Hepatic artery catheter MDCT is an invasive procedure that involves injection of lipiodol into the hepatic artery. It can detect subtle intra-arterial enhancement, which may not be revealed on intravenous contrast injection. This procedure could thus have a significant impact on tumor treatment options.

Detection of Small Benign Lesions

The differentiation between tiny benign and malignant lesions poses a challenge for MDCT. The only factor that is of vital importance to consider is the pattern of enhancement following administration of contrast. Thinner collimation with MDCT helps in accurate detection of attenuation in tiny lesions such as simple cysts. MDCT also aids in better differentiation of hemangiomas from hypervascular metastasis. Attenuation of small hemangiomas is more or less like that of the aorta in the arterial phases and similar to the hepatic veins.

Importance of Early Tumor Detection by MDCT

Early detection of small hypervascular metastases and primary tumors by MDCT is important for tumor mass. It is also an important imaging modality for tumor staging (Figs. 4 and 5).

An important feature of the hepatic arterial phase for such lesions is the search for arteriportal shunting. Certain malignant lesions reveal the presence of arteriportal shunts (Fig. 6). This is due to the compression of portal or hepatic veins, which causes development of hepatic artery to portal venous collateral vessels. However, such shunts can also be visualized in the arterial phase in cases of abscess, small hemangiomas, and cirrhosis [22].
in the venous phase. As MDCT can better define arterial and venous phases, detection of tiny hemangiomas is simplified to some extent.

Due to the capability of MDCT to highlight liver contrast in different phases of the scan, the detection of focal nodular hyperplasia (FNH) is also simplified. The hallmark of FNH on dual-phase MDCT is its intense enhancement pattern, with or without a low attenuation central area, on arterial phase images and rapid wash out on venous phase images, in which it becomes more or less isoattenuating with the liver [26, 27] (Fig. 7).

**MDCT in Liver Cirrhosis**

With the availability of smart prep technology in the recent 16- and 64-slice scanners, the arterial and venous phases can be optimally timed, which is of paramount importance in cirrhotic patients who have decreased liver perfusion. In addition, the use of high-concentration contrast medium enables better visualization of the heterogeneous enhancement pattern in cirrhotics, which is mainly due to regenerative nodules, periportal fibrosis, and microcirculatory shunts between the portal venous and hepatic venous systems. Due to the thin slice collimation and accurate definition of the arterial and venous phase with MDCT scanners, better image quality and CTA reconstructions from data sets are possible. The collateral circulation in cases of portal hypertension is also seen more clearly and with prominent paraumbilical collaterals, esophageal varices, and periportal circulation.

**MDCT for Preoperative Planning**

Preoperative knowledge of the variations in vascular anatomy could help avoid complications such as inadvertent ligation or injury of various hepatic arteries, hepatic ischemia, and hemorrhage and biliary leak. Variations in the celiac axis anatomy are common, and preoperative knowledge is useful for surgery, especially in obese patients who have large amounts of lymphatic and fatty tissue in the duodenal hepatic ligament and the porta hepatitis [28]. CT angiography images can provide excellent outlining of the vascular struc-
and demonstrate the exact extent of involvement by lesions. CTA images are especially useful for understanding vascular variations prior to hepatic resection and the extent of vascular involvement by tumors before liver surgery (Fig. 8).

The newer MDCT scanners enable routine acquisition of submillimeter sections (up to 0.5 mm) with isotropic resolution [29, 30]. The quality of the three-dimensional (3-D) images is largely dependent on the source images for reconstruction. As with other forms of visualization, such as multiplanar reformation (MPR), volume rendering (VR), and maximum intensity projections (MIP), the source images should be of thin collimation, have a greater longitudinal coverage with about 50% overlap, and sufficient signal-to-noise ratio. These prerequisites are well provided by recent MDCT scanners [31].

The usual techniques for CT angiography of the liver are VR and MIP [32]. The MIP images provide no clue as to the depth of the structure but project the brightest structure, which in the hepatic arterial phase is the vascular detail (Fig. 9). Hence, optimal delay time, contrast medium concentration, and opacification are important. Due to the inherent capability of MDCT to provide desirable volumetric data and the required overlap, the reconstructed MIP images are of better quality than those obtained from older CT scanners. Some MDCT vendors allow users to save simplified scanning protocols on the user interface in the scanner so that exquisite MIP images can be obtained directly at the console.

Conclusion

MDCT offers several advantages, such as increased scanning speed and better definition of lesion conspicuity and characterization. However, to realize the maximum benefit, optimization of the acquisition parameters in different scanner types is important. Dual-phase imaging of the liver on MDCT is usually performed in the late arterial and portal venous phases, which not only enables better detection of small hypervascular lesions (in the arterial phase) at an early stage, but also plays an important role for early treatment planning. The availability of high-iodine concentration contrast medium (≥370 mg/I/ml) is an added benefit in
such settings. These contrast media not only provide better opacification of vascular structures but also add to the quality of reconstruction images, especially for preoperative planning and placement of intra-arterial pumps [33–35]. To ensure better-quality images, technical details pertaining to planning scan delays and the right time of arterial contrast delivery are important.

References


A retrospectively ECG-gated multislice spiral CT scan and reconstruction technique with suppression of heart pulsation artifacts for cardio-thoracic imaging with extended volume coverage. Eur Radiol 12(6):1497–1503


