Journal of Surgical Research **160,** 236–243 (2010)
doi:10.1016/j.jss.2009.04.050

Exact CT-Based Liver Volume Calculation Including Nonmetabolic Liver Tissue in Three-Dimensional Liver Reconstruction

Sascha A. Müller, M.D.,* Karin Bläuer, M.D.,† Michael Kremer, M.D.,* Matthias Thorn, Ph.D.,‡ Arianeb Mehrabi, M.D.,* Hans-Peter Meinzer, Ph.D.,‡ Ulf Hinz,§ Jürg Metzger, M.D.,† Markus W. Büchler,* and Bruno M. Schmied, M.D.*,[1]

*Department of General, Visceral, and Transplant Surgery, University of Heidelberg, Heidelberg, Germany; †Department of Surgery, Kantonsspital Luzern, Luzern, Switzerland; ‡Department of Medical and Biological Informatics, German Cancer Research Center, Heidelberg, Heidelberg, Germany; and §Unit for Documentation and Statistics, Department of Surgery, University of Heidelberg, Heidelberg, Germany

Submitted for publication September 14, 2008

Exact preoperative determination of the liver volume is of great importance prior to hepatobiliary surgery, especially in living donated liver transplantation (LDLT) and extended hepatic resections. Modern surgery-planning systems estimate these volumes from segmented image data. In an experimental porcine study, our aim was (1) to analyze and compare three volume measurement algorithms to predict total liver volume, and (2) to determine vessel tree volumes equivalent to nonmetabolic liver tissue. Twelve porcine livers were examined using a standardized three-phase computed tomography (CT) scan and liver volume was calculated computer-assisted with the three different algorithms. After hepatectomy, livers were weighed and their vascular system plasticized followed by CT scan, CT reconstruction and re-evaluation of total liver and vessel volumes with the three different algorithms.

Blood volume determined by the plasticized model was at least 1.89 times higher than calculated by multislice CT scans (9.7% *versus* 21.36%, $P = 0.028$). Analysis of 3D-CT-volumetry showed good correlation between the actual and the calculated liver volume in all tested algorithms with a high significant difference in estimating the liver volume between Heymsfield *versus* Heidelberg ($P = 0.0005$) and literature *versus* Heidelberg ($P = 0.0060$). The Heidelberg algorithm reduced the measuring error with deviations of only 1.2%. The present results suggest a safe and highly predictable use of 3D-volumetry in liver surgery for evaluating liver volumes. With a precise algorithm, the volume of remaining liver or single segments can be evaluated exactly and potential operative risks can therefore be better calculated. To our knowledge, this study implies for the first time a blood pool, which corresponds to nonmetabolic liver tissue, of more than 20% of the whole liver volume.

Key Words: **liver volumetry; hepatic blood pool; vessel tree; algorithm; living donor liver transplantation.**

INTRODUCTION

The accurate calculation of preoperative liver volumes has important relevance to both contemporary transplant and oncologic liver surgery. Improvements in surgical techniques, anesthetic protocols, and perioperative care resulting in decreased morbidity and mortality rates has contributed to an increase in surgery for primary and secondary hepatic malignancy [1]. Although the rates of adverse outcomes are low, patients undergoing large resections continue to be at risk of inadequate functional residual liver tissue [2]. In noncirrhotic livers, resection of about 70% to 80% of total liver volume can be tolerated, presuming that there is sufficient arterial and portal venous supply, and no impairment of hepatic venous outflow and biliary drainage of the entire remnant [2–4]. Total liver volume is reported to have a relatively constant relation to body weight, ranging between 2% and 2.7% in healthy subjects [5].

In live donor liver transplantation (LDLT), transfer of inadequate liver cell mass leads to high morbidity with unacceptable mortality rates [6]. The exact amount

[1] To whom correspondence and reprint requests should be addressed at Department General, Visceral, and Transplantation Surgery, University of Heidelberg, im Neuenheimer Feld 110, D-69120 Heidelberg, Germany. E-mail: bruno.schmied@med.uni-heidelberg.de.

0022-4804/09 $36.00

of liver necessary to minimize the risk of liver dysfunction with altered hepatic parenchyma postoperatively remains unclear. The Urata formula is most commonly used in Asia to calculate the recipient's standard liver volume [7]. In European countries, liver volume is generally calculated with the graft-recipient body weight ratio (GRWR) and is desired to be 1% or more. A small graft may not sustain metabolic function in the recipient, but a large graft may lead to graft compression and poor perfusion [8]. The basic assumption for successful LDLT is the realization of adequate liver parenchyma for both the recipient and the donor [9, 10].

Donor safety must always be the primary consideration. Liver remnant volume of approximately 30% of the total liver volume is sufficient for the donor to survive, provided that the liver parenchyma is normal without evidence of fatty infiltration or fibrosis [11, 12].

To minimize the risk of postoperative liver failure, preoperative estimation of the residual liver function has become a fundamental part of liver surgery [13–16]. Recent advances in imaging techniques allow three-dimensional (3D) modeling of the liver with accurate liver segmentation and visualization of the liver segments with their arterial and venous supply and biliary drainage [17, 18]. Classification proposed by Couinaud is a widely accepted mean of establishing the surgically relevant segmental anatomy of the liver [19], but clinical studies have demonstrated that the radiological shape and localization of these segments does not always match the actual parenchymal condition [20, 21].

Heymsfield *et al.* first described the method of hepatic volumetry, which became the gold standard for liver volume calculation [22]. Since its introduction in the late 1970s, several new visualization techniques and refinements in semiautomatic liver volumetry have been developed [23, 24]. These are established in the clinical routine, although it is not uncommon that computer systems over- and underestimate real volumes [25, 26] affecting the tightly calculated liver reserve for both graft and remnant livers.Preoperative liver volume assessment by computed tomography (CT) or magnetic resonance imaging (MRI) is associated with an estimation error of 5% to 36% compared with intraoperatively measured actual graft weights [26, 27]. None of the computer systems take into account the presence of nonmetabolic liver tissue defined as the vascular and biliary tree, which has no metabolic liver function. The aim of this study was to analyze and compare two established volume measurement algorithms with our new algorithm. Our own experience in liver surgery and review of the literature have shown that preoperative volume calculation is often inadequate and can lead to fatal consequences, especially in living-related liver transplantation [25–27]. We therefore designed a new algorithm in an attempt to improve the calculations of preoperative and remnant liver volume. Based on the results presented in this study, we introduced this method in our LDLT and major hepatic resection program. Further nonselective comparison of algorithms in different intuitional cohorts is needed to clinically validate this new technique.

Due to the high resolution and the visualization of the vascular tree, we were interested to evaluate the magnitude of nonmetabolic liver volume, such as the portal venous and arterial vessel tree representing nonmetabolic liver tissue. Livers with anatomic variations, such as livers with accessory hepatic arteries or livers with portal hypertension, fatty changes, fibrosis, or especially cirrhosis, show a different proportion of functional and nonfunctional liver tissue to normal livers.

MATERIAL AND METHODS

Animals

Twelve female German landrace pigs weighing 30 to 35 kg that had access to food and water *ad libitum* were fasted for 12 h before the study. They were housed at the Animal Resource Service Facilities at the University of Heidelberg according to the procedures outlined in the Guide for the Care and Use of Laboratory Animals, prepared by the National Academy of Sciences. The anesthetic protocol we followed is standardized and has been used for many years in different porcine studies [28, 29]. After initial sedation by intramuscular injection of 5.0 mg/kg ketamine hydrochloride (Ketanest S; Pfizer, Freiburg, Germany), 0.1 mg/kg midazolam (Dormicum; Roche, Mannheim, Germany), and 0.5 mg/kg azaperon (Stresnil; Jansen-Cilag, Neuss, Germany), general anaesthesia was induced with tracheal intubation and a mixture of oxygen, nitrous oxide and isoflurane (Abbott, Chicago, IL). The animals then underwent sequential CT Scan and total hepatectomy. Between the CT scan and the hepatectomy, no intravenous fluids were administered. CT scan and hepatectomy were performed within 60 min after intubation. Furthermore, we continuously measured the central venous pressure and recorded stable pressures of 8 to 10 cm H_2O during the procedure in all 12 pigs.

CT Scan

Helical CT scans were performed using a Volume Zoom Somatom Plus 4 single-slice scanner (Siemens, Erlangen, Germany) with 2.5 mm collimation. First, a native abdominal sequence was performed. Hereafter, a cholangiography was carried out after administration of 30 mL Biliscopin (Schering, Berlin, Germany) intravenously for intrahepatic bile duct examination. Afterwards, we performed a multislice CT after i.v. injection of 80 mL nonionic contrast medium (Ultravist; Schering, Berlin, Germany) at a rate of 5 mL/s. The region-of-interest cursor for bolus tracking was placed in the aorta at the level of the diaphragmatic dome. With a table speed of 15 mm per rotation, arterial phase scans were obtained after bolus tracking, portal dominant phase images after 20 s, and portovenous phase after 50 s. Axial images were reconstructed using a standard algorithm, postprocessing was performed on a commercially available workstation (Chili; Heidelberg, Germany). All helical images were reconstructed at 3 mm interval.

Volumetric Analysis

One observer (MT) segmented all CT-images semiautomatically on the axial portal venous phase images to determine total liver volume