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ORIGINAL ARTICLE

Novel three-dimensional imaging technique improves the accuracy of hepatic volumetric assessment

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Abstract

Background: With pre-operative prediction of liver volume becoming increasingly important to safely carry out complex hepatic resections, the aim of the present study was to validate the accuracy of a three-dimensional (3-D) liver surgery operative planning software in performing hepatic volumetry.

Methods: Between 1999 and 2007, we performed 29 live donor liver resections for transplantation. Eleven patients had pre-operative volumetry performed by radiologists from either computed tomography (CT) or magnetic resonance (MR) imaging with documentation of the corresponding specimen weight. Retrospectively, images were uploaded into Scout™ where 3-D models of each case were generated to perform volumetry. A correlational analysis was performed followed by an accuracy comparison.

Results: Estimations by both radiologists and Scout™ were significantly correlated with the specimen weights, $P \leq 0.0001$. Compared with radiologists' volumetry, Scout™ significantly improved overall accuracy [per cent error (PE) 20.0% ± 5.3 vs. 32.9% ± 5.7, $P = 0.005$], accuracy of CT-based estimations (PE 23.2% ± 6.7 vs. 37.2% ± 6.9, $P = 0.023$) and accuracy of the left lateral section (PE 11.1% ± 3.9 vs. 26.6% ± 6.8, $P = 0.027$).

Discussion: This 3-D planning software is a valid tool for use in volumetry. Significance is greatest for CT-based models of the left lateral section. This approach gives surgeons the ability to assess volumetrics and actively plan resections.

Keywords

resection < liver, post-operative dysfunction and ischaemia re-perfusion < liver

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Introduction

Hepatectomy is becoming an increasingly important therapeutic modality. Although an aggressive surgical approach has improved the long-term survival of patients with many primary and secondary hepatic tumours, the rates of post-operative hepatic insufficiency and/or liver failure are increasing as the degree of resection is extended.[1–5] Likewise, precise knowledge of volumes is imperative for performing resections in the setting of living donation. Small grafts or excessive resections can result in hepatic failure in the recipient or donor, respectively.[6] Liver surgeons often face the difficult challenge of properly selecting patients' resection, especially with close surgical margins and marginal remnant volumes.

The size of the future liver remnant is an accurate predictor of dysfunction after liver resection.[2] In patients with normal liver parenchyma, most experts recommend preserving approximately 25% of the functional residual volume to avoid post-operative hepatic insufficiency.[2] The recommended volume increases to 40% in the setting of high-grade steatosis (>30% of hepatocytes containing macrovesicular lipid vacuoles) and is greater than 50% in patients with well-compensated cirrhosis (and absence of portal hypertension).[7–10]

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Allografts procured from live donors should be size matched to meet the metabolic needs of the recipient. A minimum graft-to-recipient weight ratio of 0.8% is recommended to prevent small-for-size syndrome in adult recipients.[11] Whether for disease or donation, an accurate assessment of hepatic volumetry is necessary to individualize risk and improve the safety of liver resections.

Several methods have been developed to estimate liver volume and predict the size of the future remnant. Conventional planimetry utilizes individual cross-sectional areas of interest, which can then be summed to yield volumes.[12] It can be performed at the time of scanning by radiologists and does not require any additional equipment or software.

Whereas volumetry can easily be performed using conventional planimetry, to understand the spatial relationships between tumours and vasculature structures, 3-D hepatic modelling systems have been developed. Three-dimensional modelling from axial images affords precise topographic and volumetric information pre-operatively, which is useful in surgical decision-making as well as operative planning.[13,14] The majority of these systems, however, are 'plug-ins' to hardware devices [computed tomography (CT) and magnetic resonance imaging (MRI) scanners] and thus are limited by cost, access and interpretation by expertly trained radiologists. Some remote programs that can be operated independently from radiologists have recently been developed.[8,15,16]

Here we report the results of a novel 3-D imaging program that serves to validate its use in the pre-operative assessment of liver volume. The software is remotely accessible and can be utilized by non-radiologists to give accurate topographic and volumetric assessments.

Methods

This retrospective study was conducted under the Human Studies Protocol with approval from the Human Research Protection Office (HRPO) of Washington University in Saint Louis, USA.

Patient population

Twenty-nine live donor liver resections for transplantation were performed at Barnes-Jewish Hospital/Washington University School of Medicine between 1999 and 2007. Among these patients, 11 had pre-operative volumetry performed by radiologists along with documentation of the corresponding weight of each resection at the time of live donor transplant. A significant cohort of excluded patients (Table 1) underwent a left lateral sectionectomy without pre-operative volumetry for donation to paediatric recipients. Allograft regeneration or diminution has been shown to occur rapidly in children, which made volumetry less important in this population.[17] Patients analysed underwent a right hepatectomy, a left lateral sectionectomy or a left hepatectomy according to the segmental classification of the liver as described by Couinaud.[18]

Table 1 Excluded patients (n = 18)

Characteristic	n
Donation of the left lateral section for the paediatric recipient	6
Imaging not accessible for retrospection	5
Donation preceded practice of routine volumetry	4
Volumetry performed did not correspond to resection	2
Absence of specimen weight	1

Volumetry

All patients underwent axial abdominal imaging as part of their routine pre-operative donor evaluation with either intravenous contrast-enhanced CT or MR imaging. Standard liver protocols for both modalities included triple phase imaging with a slice thickness of 5 mm and 8 mm for CT and MR, respectively. Radiologists employed either conventional planimetry or an integrated modelling system to perform volumetry. Total hepatic volume as well as the planned resection volume was estimated by radiologists before the planned resections.

Novel volumetric alternative

Retrospectively, the same axial images were uploaded into a novel simulation software system for modelling. Developed by Pathfinder Therapeutics, Inc. (Nashville, TN, USA), the Scout™ system was designed to give radiologists and non-radiologists the ability to create 3-D models in order to pre-operatively assess volumetrics and plan for resections (Fig. 1). Approved for use by the Food and Drug Administration (FDA), the software can be loaded onto a laptop computer and operated remotely. In the present study, a non-radiologist novice (no previous experience with Scout™ software) received instruction regarding the program's basic functionality by an experienced user. Novel algorithms provide semi-automatic segmentation of the liver, tumours and vasculature from a series of axial images.[19] After the initial segmentation, a brief evaluation and user-interaction phase allows for precision contouring. Three-dimensional rendering of the final segmentation generates the model, which can then be manipulated by the user for operative planning. Resection planes with margin maps can be created in addition to the calculation of hepatic volumes. While blinded to the specimen weights, the novice utilizing Scout™ software estimated the volumes of each resection.

Validation

The validity of hepatic volumetry was evaluated with a Pearson's test to determine whether a significant correlation existed between the estimated volumes and the actual weights of the corresponding specimens. A correlational curve was developed for both radiologists and the novice utilizing Scout™.

Comparison

The weights of the resected specimens were divided by a standardized liver density (1.05 g/ml) in order to determine their respec-

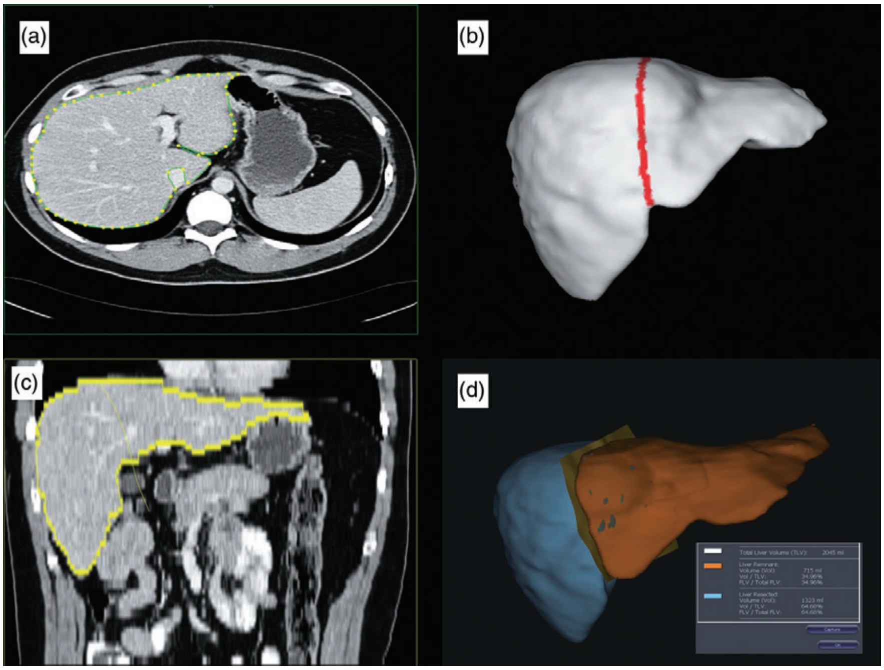

Figure 1 Three-dimensional (3-D) simulation of a right hepatectomy utilizing Scout™ Software. (a) Novel algorithms provide semi-automatic segmentation of axial images. Users can then interface with the software to optimize contours. (b) Resection plane drawn after rendering of a 3-D model. C. Resection planes are projected onto 2-D images and can be adjusted in accordance with the operative plan. (d) Volume rendering after simulation of the resection

tive volumes, which was the measure utilized by the respective volumetric systems [liver weight (g) ÷ liver density (1.05 g/ml) = liver volume (mL)].[20] Then, the estimations of the resected volumes by radiologists were compared with the estimations by the novice utilizing Scout™. The accuracy of both groups was evaluated by calculating the absolute error, which was normalized for size to obtain the absolute percentage error for each case.[21]

$$\text{absolute error} = |\text{predicted volume} - \text{true volume}|$$

$$\text{percentage error } \% = [|\text{predicted volume} - \text{true volume}| \div \text{true volume}] \times 100$$

Comparisons were stratified to determine whether differences in axial imaging modality or resection type had an effect on the accuracy of either group.

Statistics

Statistical analyses were conducted using GraphPad software, San Diego, CA, USA. Differences between groups were compared using a paired Student's *t*-test. All data are expressed as mean ± standard error of the mean (SEM). *P*-value <0.05 was considered significant. The statistical power of each *t*-test was also calculated utilizing Decision Support System, LP software to determine the β-level for each test.

Results

Patients

All patients included in the present study ($n = 11$) had normal underlying liver function before donor hepatectomy. Pre-operative imaging consisted of either an abdominal CT ($n = 8$) or MRI ($n = 3$). Donor operations included a right hepatectomy ($n = 5$), a left lateral sectionectomy ($n = 5$) or a left hepatectomy ($n = 1$).

Validation

Both groups performing volumetry produced significant positive correlations between their estimated volumes and the actual weights of the corresponding resection specimens (Fig. 2).

Accuracy comparison (Table 2)

The overall accuracy of volumetric assessment was significantly improved using Scout™ software, $P = 0.005$. In spite of a small cohort of patients, a novice utilizing Scout™ for the first time gave more accurate estimations of hepatic volumes than radiologist predictions. However, given variability in pre-operative imaging modality from which the volumetry was performed and the resection type, we further stratified our results.

In differentiating the type of axial imaging used in volumetry, we found that the accuracy of CT-based estimations were significantly improved by Scout™ compared with radiologists, $P = 0.023$. The accuracy of the volumes calculated from MR ($n = 3$) was

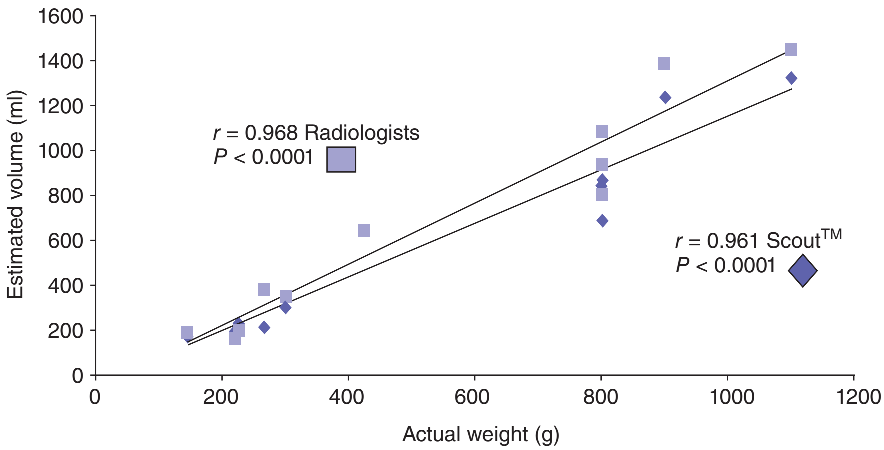

Figure 2 Correlational analysis. Both groups produced significant positive correlations between their estimated volumes and the actual weights of the resected specimens

Table 2 Stratification of accuracy

Accuracy (PE)	Factor	Radiologists	Scout™	P	n	α (type I error)	β (type 2 error)
Imaging modality	Overall	32.9 ± 5.7	20.0 ± 5.3	0.005	11	0.05	0.623
	CT	37.2 ± 6.9	23.2 ± 6.7	0.023	8	0.05	0.694
	MR	21.3 ± 8.1	11.6 ± 6.2	0.112	3	0.05	0.841
Resection specimen	Left lateral section	26.6 ± 6.8	11.1 ± 3.9	0.027	5	0.05	0.492
	Right hemiliver	33.8 ± 9.5	21.3 ± 6.5	0.120	5	0.05	0.806

PE, percentage error (%); CT, computed tomography; MR, magnetic resonance.

improved by Scout™ software; however, the difference did not reach statistical significance ($P = 0.112$, $\beta = 0.841$).

Finally, we studied how the anatomic conditions of the resected specimen may have affected the accuracy of the two groups. The accuracy of the left lateral section volume was significantly improved by Scout™ compared with radiologists, $P = 0.027$. Improvement using the Scout™ system was not significant for estimating right hepatectomy volume, $P = 0.120$, $\beta = 0.806$.

Discussion

Although the peri-operative safety of liver surgery has drastically improved in recent decades, post-operative complications from extended liver resections continue to be a major concern.[2] Simulating the operative plan with modelling software is a useful method for surgeons to engage themselves in the radiographical phase of pre-operative assessment. Given that functional residual volume is one of the most important prognostic factors in liver resection surgery, it behooves surgeons to participate in its assessment in order to achieve optimal risk reduction before carrying out complex resections.

Our preliminary data seemed to indicate that there was a greater improvement from CT-based models of the left lateral section. There are several possible explanations for this observation. First, the present study is a retrospective analysis of a limited number of patients. Variability among the donors in their pre-operative imaging and resection type calls for a subgroup analysis to account for these factors in an accuracy comparison. However, the cohorts were quite small, which made showing statistical improvements by Scout™ difficult across all conditions. Second, the falciform ligament makes the resection plane of the left lateral section more uniform, thus making the model more likely to correlate with the resection. Given that the distinction between the right and left lobe of the liver is functional rather than anatomical, a non-surgeon may have difficulty rendering an accurate resection plane. As we move into prospective investigations, we will attempt to answer this question more definitively.

Scout™ software gives surgeons the ability to accurately access hepatic volumetrics and plan resections with ease and efficiency. Invaluable information for risk stratification and surgical decision-making can be gathered and interpreted by the operating surgeon who performs their own volumetry. Whereas standard volumetry is limited by cost, access and interpretation by radiologists, Scout™ is remote, accessible and user friendly.

Accurate pre-operative assessments of hepatic volumetrics are needed for surgeons to risk stratify and properly select patients for major hepatic resections. Scout™ represents a step towards a greater accuracy in hepatic volumetrics and improved safety in liver surgery.

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Conflicts of interest

W.C.C., MD, is one of several co-founders of Pathfinder Therapeutics, Inc. (PTI) which distributes the Scout™ software.

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