LIVER TRANSPLANTATION 17:1427-1436, 2011

ORIGINAL ARTICLE

Computed Tomography Liver Volumetry Using 3-Dimensional Image Data in Living Donor Liver Transplantation: Effects of the Slice Thickness on the Volume Calculation

Masatoshi Hori,[1,2] **Kenji Suzuki,**[1] **Mark L. Epstein,**[1] **and Richard L. Baron**[1]
[1]*Department of Radiology, University of Chicago, Chicago, IL; and* [2]*Department of Radiology, Osaka University Graduate School of Medicine, Osaka, Japan*

The purpose of this study was to evaluate the relationship between the slice thickness and the calculated volume in computed tomography (CT) liver volumetry through the comparison of the results from images [including 3-dimensional (3D) images] with various slice thicknesses. Twenty potential adult liver donors (12 men and 8 women) with a mean age of 39 years (range = 24-64 years) underwent CT with a 64-section multidetector row CT scanner after the intravenous injection of a contrast material. Four image sets with slice thicknesses of 0.625, 2.5, 5, and 10 mm were used. First, a program developed in our laboratory for automated liver extraction was applied to the CT images, and the liver boundaries were determined automatically. Then, an abdominal radiologist reviewed all images onto which automatically extracted boundaries had been superimposed and then edited the boundaries on each slice to enhance the accuracy. The liver volumes were determined via the counting of the voxels within the liver boundaries. The mean whole liver volumes estimated with CT were 1322.5 cm^3 from 0.625-mm images, 1313.3 cm^3 from 2.5-mm images, 1310.3 cm^3 from 5-mm images, and 1268.2 cm^3 from 10-mm images. The volumes calculated from 3D (0.625-mm) images were significantly larger than the volumes calculated from thicker images ($P < 0.001$). The partial liver volumes of right lobes, left lobes, and lateral segments were evaluated in a similar manner. The estimated maximum difference in the calculated volumes of lateral segments was −10.9 cm^3 (−4.63%) between 0.625- and 5-mm images. In conclusion, liver volumes calculated from 2.5-mm-thick or thicker images are significantly smaller than liver volumes calculated from 3D images. If a maximum error of 5% in the calculated graft volume will not have a significant clinical impact, 5-mm-thick images are acceptable for CT volumetry. If the impact is significant, 3D images could be essential. ***Liver Transpl 17:1427-1436, 2011.*** © **2011 AASLD.**

Received June 1, 2011; accepted August 10, 2011.

Computed tomography (CT) liver volumetry is a technique that enables us to assess the liver volume noninvasively. The principle of this technique is simple, and it has been reported since the 1970s.[1] With this method, the volume of the liver can be calculated by (1) the measurement of the area of each cross-sectional image, (2) the multiplication of the area by the slice interval to determine the slice volume, and (3) the summing of the slice volumes to determine the total liver volume. This technique can be used for preoperative measurements of the liver volumes of donors for living liver transplantation.[2,3] For living liver transplantation, the evaluation of the total and segmental liver volumes is crucial because the graft size is one of the major factors determining a successful outcome for both the recipient and the donor.[4,5]

Abbreviations: 3D, 3-dimensional; CI, confidence interval; CT, computed tomography; *d*, thickness, interval, or height (variable); *r*, radius (variable); r_{min}, minimum radius (variable); r_{mid}, middle radius (variable); r_{max}, maximum radius (variable); *S*, slice (variable); S2, segment 2; S3, segment 3; S4, segment 4; S5, segment 5; S8, segment 8; SD, standard deviation.

This study was partially supported by the National Institutes of Health (grants S10 RR021039 and P30 CA14599).

Address reprint requests to Masatoshi Hori, M.D., Ph.D., Department of Radiology, University of Chicago, 5841 South Maryland Avenue, MC 2026, Chicago, IL 60637. Telephone: +1 773 702-6154; FAX: +1 773 702-0371; E-mail: mhori@radiol.med.osaka-u.ac.jp

DOI 10.1002/lt.22419
View this article online at wileyonlinelibrary.com.
LIVER TRANSPLANTATION.DOI 10.1002/lt. *Published on behalf of the American Association for the Study of Liver Diseases*

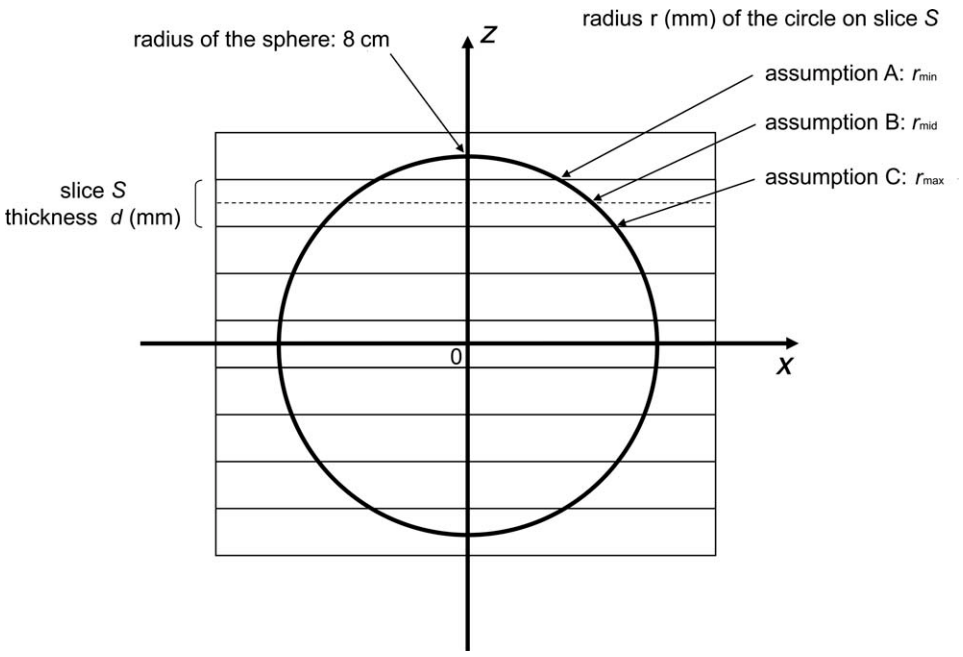

Figure 1. This drawing of the spherical model used for the numerical simulation shows a cross-section of a sphere with a radius of 8 cm at $y = 0$. The y axis is perpendicular to the plane of the paper. The center of the sphere is located at the origin of the coordinate system. The rectangles show cross-sections of CT slices, which are perpendicular to the z axis; both the thickness and the intervals are d millimeters. The center of the sphere is located in the middle of a slice and at the center of the slice plane. For a given slice S, the volume of a part of the sphere within slice S can be approximated by the volume of a cylinder with a radius of r millimeters and a height of d millimeters. The volume of the cylinder was calculated on the basis of 3 assumptions for the radius: (A) r_{min}, (B) r_{mid}, and (C) r_{max}. The total volume of the sphere was approximated as the sum of the volumes of these cylinders.

Using intraoperative liver volume measurements as the reference standard, many researchers have reported results for the accuracy of CT liver volumetry. With respect to the accuracy of the technique, the reported results have shown deviations from the reference standard that range from 0% to more than 30%.[6-10] Some of the errors are considered to be due to partial volume effects. The volume of each slice has an inherent error due to partial volume effects, and the errors are potentially cumulative when the slice volumes are added to calculate the total liver volume. A quantitative estimation of the degree of the error could be useful for improving the accuracy of CT liver volumetry.

Recent advances in multidetector row helical CT technology have enabled us to obtain isotropic 3-dimensional (3D) image data with a typical slice thickness of 0.5 to 0.7 mm. With the use of 3D image data, partial volume effects are expected to decrease considerably, and the accuracy of CT liver volumetry potentially can be improved. On the other hand, the workload (time) of radiologists or surgeons will be substantially greater if they need to manually trace the liver contours on each 3D image instead of the usual 2-dimensional images because of the considerable increase in the number of images when thinner slice sections are used. To our knowledge, there are no published reports on CT liver volumetry with 3D image data, and no studies have systematically made quantitative estimates of the effects of slice thicknesses less than 1 mm (ie, 3D image data) on volume calculations; however, some researchers have studied the effects of slice thicknesses as low as 2 mm.[11] Therefore, it is unclear whether using 3D data would provide more accurate measurements and would, therefore, be the preferred technique for CT volumetry in clinical routines.

The purpose of this study was to evaluate the relationship between the slice thickness and the calculated volume in CT liver volumetry through the use of a numerical simulation based on a simple model and through the comparison of CT volumetry results from images with various slice thicknesses (including 0.625-mm-thick isotropic 3D images).

MATERIALS AND METHODS

The institutional review board approved this Health Insurance Portability and Accountability Act–compliant retrospective study and waived the requirement for informed consent.

Numerical Simulation

In order to examine the effects of the slice thickness on the accuracy of volumetry, we performed a numerical simulation based on a simple model. In this simulation, the volume of a sphere with a radius of 8 cm was calculated (Fig. 1). We used a sphere instead of the actual liver shape in this simulation because we thought that it would be adequate for a rough estimation of the effects being studied.

The rectangles in Fig. 1 show cross-sections of CT slices with thicknesses and intervals of d millimeters. The center of the sphere is located in the middle of a slice and at the center of the slice plane. For a given slice S, the volume of a part of the sphere within slice S can be approximated by the volume of a cylinder with a radius of r millimeters and a height of d millimeters. The volume of the cylinder was calculated on the basis of 3 assumptions for the radius: (A) the minimum value (r_{min}), (B) the middle value (r_{mid}), and (C) the maximum value (r_{max}). The minimum and maximum distances between the z axis and the surface of the sphere in slice S (ie, r_{min} and r_{max}) were used as the cylinder radii for the minimum and maximum assumptions, respectively. For the middle assumption, the distance between the z axis and the surface of the sphere at the middle of slice S (ie, r_{mid}) was used as the cylinder radius. The total volume of the sphere was approximated as the sum of the volumes of these cylinders. The true volume of the sphere should lie between the values calculated with the minimum and maximum assumptions. As the slice thickness/interval decreases, the difference between the values of the minimum and maximum assumptions will also decrease.

Potential Liver Donors

Between January 2006 and March 2007, 37 consecutive potential donors for living liver transplantation were examined with 64-section multidetector row helical CT. The exclusion criteria included a fatty liver (n = 8), benign or malignant liver tumors (n = 8), and liver cysts more than 2 cm in diameter (n = 1). Therefore, 20 potential donors with a mean age of 39 years (range = 24-64 years), including 12 men and 8 women, were enrolled in the study. The mean body weight was 61 ± 10 kg (range = 40-82 kg), and the mean body height was 165 ± 10 cm (range = 146-178 cm). The standard liver volumes were calculated with a formula previously described by Urata et al.[12] Two of the potential donors each had 2 liver cysts that were less than 1 cm in diameter. Another potential donor had 4 liver cysts that were less than 5 mm in diameter. The remaining 17 potential donors had no focal liver lesions. The sample size was calculated for detecting a 1% difference between the liver volumes calculated from 2 image sets with a power of 0.8 and an α type I error of 0.05; a sample size of 10 was required. With this in mind, we chose a sample size of 20.

CT Examination

All potential liver donors were scanned with a 64-section CT scanner (LightSpeed VCT, GE Healthcare, Milwaukee, WI) after they fasted for at least 4 hours. The details of the protocol are shown in Table 1. All images were stored in a picture archiving and communication system.

TABLE 1. Parameters for CT Imaging

Parameter	Value
Scanning	
Detectors (n)	64
Section thickness (mm)	0.625/5
Section interval (mm)	0.625/5
Rotation time (seconds)	0.4
Helical pitch	1.375
Table movement (mm/rotation)	55
Field of view (cm)	34.5
Pixel matrix	512 × 512
Tube voltage (kVp)	120
Tube current (mA)*	100-750
Approximate acquisition time (seconds)†	2 (each phase)
Contrast agent	
Type	Iohexol‡
Concentration (mg of iodine/mL)	300
Mean volume (mL)	135 (range = 94-145)
Injection rate (mL/second)	3.2-5.0

*The tube current was modulated with an automatic exposure control technique (Auto mA and Smart mA, GE Healthcare). The noise index was set to 12.

†After the acquisition of unenhanced CT images, each potential donor was administered an intravenous contrast medium and was scanned during the early arterial, late arterial, and portal venous phases. For the timing of the start of the early arterial phase imaging, a bolus-tracking technique (SmartPrep, GE Healthcare) was used, and early arterial phase scanning was started 10 seconds after the trigger threshold (50 HU) was reached at the level of the supraceliac abdominal aorta. For the late arterial and portal venous phases, the scanning delays were 22 and 64 seconds, respectively, after the trigger threshold was reached.

‡Omnipaque 300 (GE Healthcare).

Liver Volume Measurements

Portal venous phase images were used in this study. For each potential donor, 2 image sets with different slice thicknesses and intervals (0.625 mm/0.625 mm and 5 mm/5 mm) were retrieved on a personal computer (2.7-GHz Xeon Quad-Core, Intel, Santa Clara, CA). Images with a 2.5-mm thickness and a 2.5-mm interval were reconstructed from 0.625-mm/0.625-mm images through the averaging of 4 contiguous 0.625-mm images. Similarly, images with a 10-mm thickness and a 10-mm interval were reconstructed from 5-mm/5-mm images through the averaging of 2 contiguous 5-mm images. Therefore, 4 image sets with slice thicknesses of 0.625, 2.5, 5, and 10 mm were available for this study. The image intervals equaled the slice thicknesses (ie, there was no slice overlap).

First, a program for automated liver extraction was applied to 0.625-mm 3D CT images, and the liver boundaries were obtained automatically for each

case. The software was developed in the our laboratory with 3D geodesic active contour segmentation coupled with a level-set algorithm.[13,14] Second, an abdominal radiologist with 15 years' experience in hepatobiliary imaging reviewed every eighth image (5-mm intervals) on which automatically extracted boundaries had been superimposed. The radiologist edited the boundaries to enhance the accuracy of the volumetry with a specially designed software tool that was developed in the our laboratory laboratory. In other words, the radiologist edited the boundaries on a 0.625-mm 3D image, skipped 7 images, edited the boundaries of another image, and then repeated the procedure. Third, the program for automated liver extraction was again applied to the images. This time, the process retained the manually corrected contours on every eighth slice, and none of the manual corrections were lost in the process. Fourth, the radiologist edited the contours on every fourth slice (2.5-mm intervals). Fifth, the automated liver extraction program was applied again, and the manually corrected contours were retained. Finally, the radiologist edited the boundary on every slice, and the contours of every slice were determined for the 0.625-mm 3D image set. The manual correction process was performed carefully, and the mean time required for its completion per case was 98 minutes (range = 85-122 minutes). The inferior vena cava, the main trunk and bilateral first branches of the portal vein, and the major fissures were excluded during the manual editing process (Fig. 2). The hepatic veins were included in the liver region. Then, the contours of 0.625-mm 3D images were transferred to the 2.5-, 5-, and 10-mm image sets. The radiologist edited the contours of every slice for these thicker images, and the contours of every slice were determined for the 2.5-, 5-, and 10-mm image sets. The whole liver volume was determined via the counting of the voxels within the liver boundaries in each case. Additionally, the radiologist drew the borders between the liver segments on CT images in a similar fashion. Then, the volumes of right lobes [Couinaud segment 5 (S5) to segment 8 (S8)], left lobes [segment 2 (S2) to segment 4 (S4)], and lateral segments [S2 and segment 3 (S3)] were also determined.

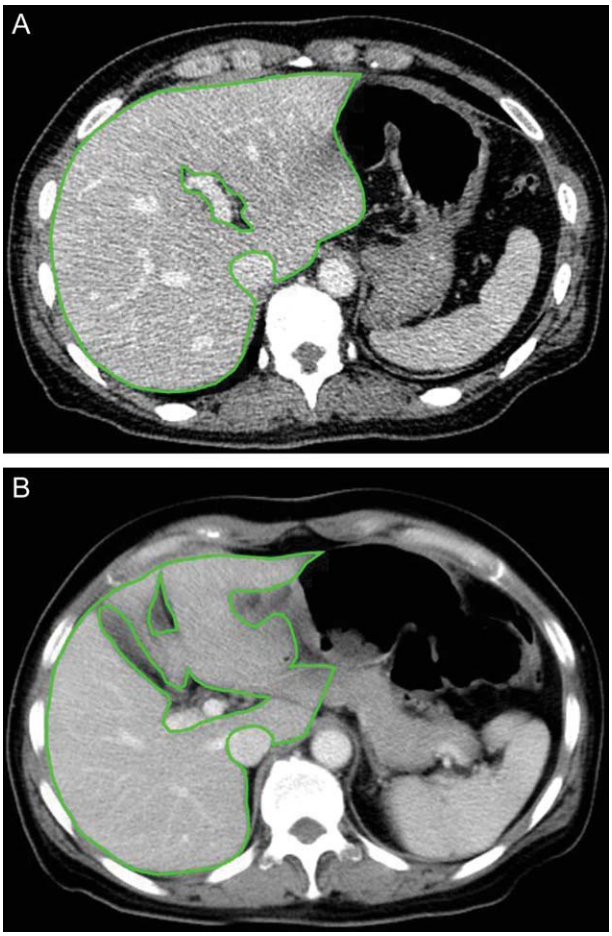

Figure 2. Liver contours on axial CT images after manual editing show the isolation of the liver from the surrounding structures. The inferior vena cava, the main trunk and bilateral first branches of the portal vein, and the major fissures are excluded from the liver region. The contours are drawn on (A) a 0.625-mm 3D image and (B) a 10-mm image. Partial volume effects are much more prominent on the 10-mm image versus the 0.625-mm image.

TABLE 2. Results of the Numerical Simulation

			Differences (%)
Slice Thickness/ Interval (mm)	Assumption A: Minimum	Assumption B: Middle	Assumption C: Maximum
10	−9.143	−0.391	9.570
5	−4.634	−0.098	4.736
2.5	−2.331	−0.024	2.356
1.25	−1.169	−0.006	1.175
0.625	−0.585	−0.002	0.587

NOTE: The values are the percentage differences between the volumes of a sphere with an 8-cm radius:

$$\text{Difference } (\%) = (\text{Calculated volume based on the simulation} - \text{Exact volume})/\text{Exact volume} \times 100$$

The exact volume of the sphere was $(4/3)\pi \times 8^3$ or 2144.66 cm^3.

Statistical Analysis

The calculated volumes from image sets with different slice thicknesses were compared. The differences between the image sets in terms of the mean calculated liver volume were analyzed statistically with a multiple-comparison analysis (Dunnett pairwise multiple-comparison *t* test). In this test, the 0.625-mm 3D image set was chosen as the control group against which the other 3 image sets (2.5-, 5-, and 10-mm images) were compared. Statistical analyses were performed with SPSS 11.0 for Windows (SPSS, Inc., Chicago, IL). A 2-tailed *P* value less than 0.05 was considered to indicate a statistically significant difference.

The statistical analysis for assessing the agreement between the volumes calculated with the 4 different image sets was performed with the method described by Bland and Altman.[15,16] The intraclass correlation coefficients were also calculated as a measure of the agreement.

RESULTS

The results of the numerical simulation are presented in Table 2. When a slice thickness of 10 mm was employed, the numerical simulation showed that the maximum difference between the exact volume of a sphere with an 8-cm radius and the calculated value based on simulations was 9.570% (assumption C), although it was less than −0.4% when the contour of the middle of the slice was used for the calculation (assumption B). The maximum difference was reduced when the slice thickness was reduced, and it was less than 0.6% when the slice thickness was 0.625 mm.

For the potential liver donors, the liver volumes estimated with CT liver volumetry are displayed in Table 3. The intraclass correlation coefficients were 1.000 (0.625-mm images versus 2.5-mm images), 1.000 (0.625-mm images versus 5-mm images), and 0.999 (0.625-mm images versus 10-mm images) for whole liver volumetry, and the differences were statistically significant ($P < 0.001$). Scatter plots showed excellent agreement between the calculated whole liver volumes from 0.625-mm images and 2.5-, 5-, and 10-mm images (Fig. 3), although the calculated volumes from 0.625-mm 3D images were significantly larger than those from thicker slice images (2.5-, 5-, and 10-mm; $P < 0.001$ for all comparison pairs). Bland-Altman plots showed no discrepancies with respect to the sizes of the whole liver volume measurements, and a thinner slice thickness showed a smaller degree of dispersion around the horizontal axis (Fig. 4). The means, the standard deviations (SDs) of the differences, the 95% limits of agreement, the widths of the 95% limits of agreement, the 95% confidence intervals (CIs) for the bias, the 95% CIs for the lower limit of agreement, and the 95% CIs for the upper limit of agreement are summarized in Table 4 for volumes from 2.5-, 5-, and 10-mm images versus 0.625-mm 3D images.

TABLE 3. Volumes Estimated With CT Liver Volumetry (20 Cases)

Slice Thickness/ Interval (mm)	Volumes (cm^3)			
	Whole Liver	Right Lobe (S5-S8)	Left Lobe (S2-S4)	Lateral Segment (S2 and S3)
10	1268.2 ± 256.8 (843.8-1805.1)*	850.8 ± 186.1 (571.2-1237.6)*	394.3 ± 88.5 (257.7-580.0)*	218.8 ± 53.2 (145.2-329.6)*
5	1310.3 ± 260.0 (860.8-1855.8)*	870.5 ± 187.9 (581.2-1255.3)†	414.2 ± 89.8 (264.4-601.4)‡	233.4 ± 55.3 (147.8-347.1)§
2.5	1313.3 ± 257.8 (871.2-1860.0)*	873.8 ± 186.5 (590.0-1255.2)§	415.0 ± 91.5 (266.9-607.9)§	232.4 ± 54.4 (150.3-340.8)§
0.625	1322.5 ± 259.5 (879.3-1874.0)	877.0 ± 187.1 (592.1-1260.0)	419.0 ± 91.8 (270.7-608.3)	235.6 ± 55.1 (153.3-342.7)

NOTE: Values are presented as means and SDs (minimum and maximum values are shown in parentheses).
*The calculated volume was significantly larger than the volume from the 0.625-mm image ($P < 0.001$; Dunnett pairwise multiple-comparison *t* test).
†The calculated volume was significantly larger than the volume from the 0.625-mm image ($P < 0.01$; Dunnett pairwise multiple-comparison *t* test).
‡The calculated volume was significantly larger than the volume from the 0.625-mm image ($P < 0.05$; Dunnett pairwise multiple-comparison *t* test).
§Not significant ($P > 0.05$).

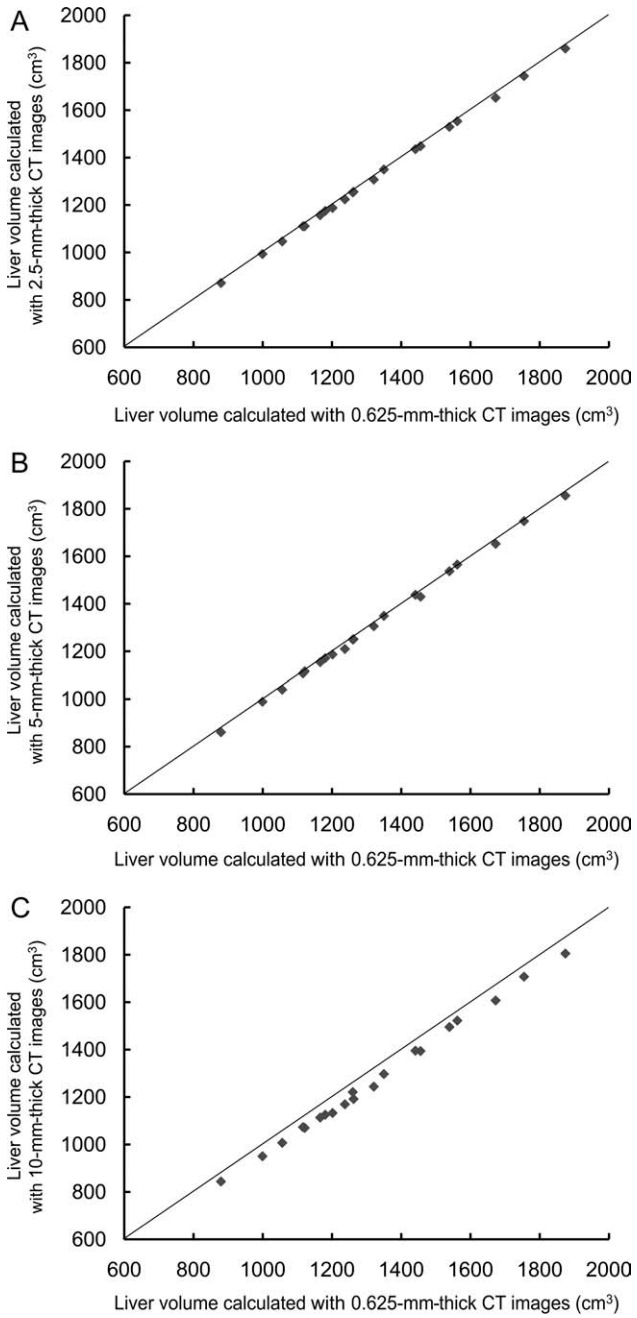

Figure 3. Scatter plots of estimated whole liver volumes from 0.625-mm 3D images versus (A) 2.5-, (B) 5-, and (C) 10-mm images. The volumes estimated from the thicker images were smaller than those estimated from the 0.625-mm images. The solid lines represent the line of equality.

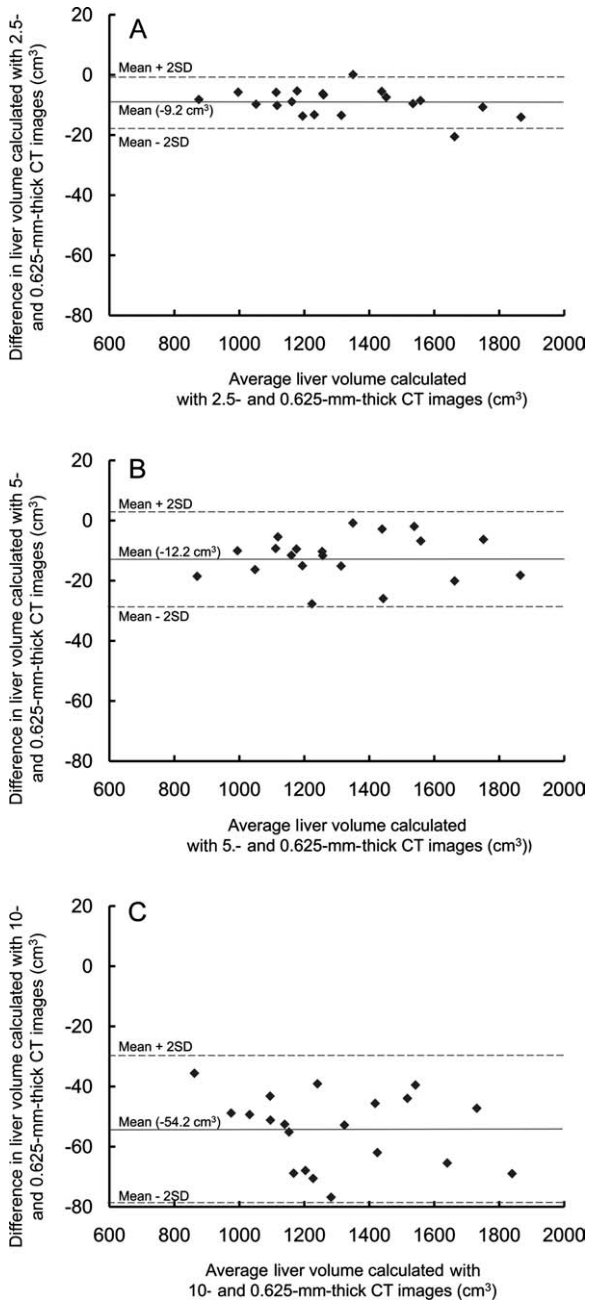

Figure 4. Plots of the differences between estimated whole liver volumes from 0.625-mm images and (A) 2.5-, (B) 5-, and (C) 10-mm images versus their averages. There were no discrepancies with respect to the sizes of the liver volume measurements. A thinner slice thickness showed a smaller degree of dispersion around the horizontal axis.

Figure 5 presents scatter plots of whole liver volumes estimated from 0.625-mm images versus standard liver volumes calculated from the body surface area. Urata et al.'s formula for the standard liver volume[12] underestimated the liver volumes, especially for patients with liver volumes greater than 1400 cm^3.

DISCUSSION

Researchers have reported that a liver recipient with a graft-to-recipient weight ratio less than 0.8% has a significantly lower chance of survival.[17] Therefore, if the graft-to-recipient weight ratio is expected to be approximately 0.8% before the operation, surgeons sometimes want to know the value with greater accuracy. In this respect, it is desirable for us to estimate the degree of error due to various factors. Although volumes calculated from 0.625-mm 3D images could be expected to be more precise than volumes calculated from thicker images because of the lower partial volume effects with 3D images, it was unclear how

TABLE 4. Accuracy Measurements for CT Liver Volumetry (20 Cases)

Variable	2.5-mm Volume Versus 0.625-mm Volume [cm^3 (%)]	5-mm Volume Versus 0.625-mm Volume [cm^3 (%)]	10-mm Volume Versus 0.625-mm Volume [cm^3 (%)]
Whole Liver			
Mean difference*	−9.2 (−0.70)	−12.2 (−0.96)	−54.2 (−4.20)
SD of differences	4.4 (0.30)	7.5 (0.61)	12.1 (1.01)
95% limits of agreement	−17.8 to −0.5 (−1.29 to −0.11)	−26.8 to 2.5 (−2.22 to 0.36)	−78.0 to −30.5 (−6.18 to −2.22)
Width of 95% limits of agreement	17.3 (1.18)	29.3 (2.58)	47.5 (3.96)
95% CI for the bias	−11.2 to −7.1 (−0.84 to −0.56)	−15.7 to −8.7 (−1.24 to −0.62)	−59.9 to −48.5 (−4.67 to −3.72)
95% CI for the lower limit of agreement	−21.3 to −14.3 (−1.53 to −1.05)	−32.8 to −20.8 (−2.75 to −1.70)	−87.7 to −68.3 (−6.99 to −5.37)
95% CI for the upper limit of agreement	−4.1 to 3.0 (−0.35 to 0.13)	−3.5 to 8.4 (−0.17 to 0.89)	−40.2 to −20.8 (−3.02 to −1.41)
Right Lobe (S5-S8)			
Mean difference*	−3.2 (−0.38)	−6.5 (−0.80)	−26.2 (−3.09)
SD of differences	3.8 (0.41)	9.6 (1.11)	12.3 (1.47)
95% limits of agreement	−10.6 to 4.1 (−1.19 to 0.43)	−25.3 to 12.2 (−2.98 to 1.38)	−50.2 to −2.2 (−5.97 to −0.21)
Width of 95% limits of agreement	14.8 (1.62)	37.6 (4.36)	48.1 (5.76)
95% CI for the bias	−5.0 to −1.5 (−0.57 to −0.18)	−11.0 to −2.1 (−1.32 to −0.28)	−31.9 to −20.5 (−3.78 to −2.40)
95% CI for the lower limit of agreement	−13.7 to −7.6 (−1.52 to −0.86)	−33.0 to −17.7 (−3.88 to −2.09)	−60.1 to −40.4 (−7.15 to −4.80)
95% CI for the upper limit of agreement	1.1-7.2 (0.10-0.76)	4.6-19.9 (0.49-2.27)	−12.0 to 7.7 (−1.39 to 0.96)
Left Lobe (S2-S4)			
Mean difference*	−4.0 (−0.97)	−4.8 (−1.09)	−24.7 (−5.95)
SD of differences	3.7 (0.73)	6.4 (1.53)	9.5 (2.02)
95% limits of agreement	−11.2 to 3.3 (−2.40 to 0.47)	−17.3 to 7.6 (−4.09 to 1.90)	−43.3 to −6.2 (−9.92 to −1.98)
Width of 95% limits of agreement	14.5 (2.86)	24.9 (5.99)	37.1 (7.94)
95% CI for the bias	−5.7 to −2.2 (−1.31 to −0.62)	−7.8 to −1.9 (−1.81 to −0.38)	−29.2 to −20.3 (−6.90 to −5.00)
95% CI for the lower limit of agreement	−14.2 to −8.3 (−2.98 to −1.81)	−22.4 to −12.2 (−5.31 to −2.87)	−50.9 to −35.7 (−11.54 to −8.30)
95% CI for the upper limit of agreement	0.3-6.3 (−0.12 to 1.05)	2.5-12.7 (0.68-3.13)	−13.7 to 1.4 (−3.60 to −0.36)
Lateral Segment (S2 and S3)			
Mean difference*	−3.2 (−1.33)	−2.2 (−0.98)	−16.8 (−7.18)
SD of differences	3.1 (1.26)	4.4 (1.86)	9.6 (4.05)
95% limits of agreement	−9.2 to 2.8 (−3.81 to 1.15)	−10.9 to 6.4 (−4.63 to 2.67)	−35.6 to 2.0 (−15.1 to 0.76)
Width of 95% limits of agreement	12.0 (4.96)	17.4 (7.29)	37.7 (15.87)
95% CI for the bias	−4.6 to −1.8 (−1.92 to −0.74)	−4.3 to −0.2 (−1.85 to −0.11)	−21.3 to −12.3 (−9.07 to −5.28)
95% CI for the lower limit of agreement	−11.7 to −6.8 (−4.82 to −2.80)	−14.5 to −7.4 (−6.11 to −3.14)	−43.3 to −27.9 (−18.35 to −11.87)
95% CI for the upper limit of agreement	0.3-5.2 (0.13-2.16)	2.9-10.0 (1.18-4.16)	−5.7 to 9.7 (−2.48 to 4.00)

*Differences were calculated via the subtraction of 0.625-mm image volumes from 2.5-, 5-, or 10-mm image volumes.

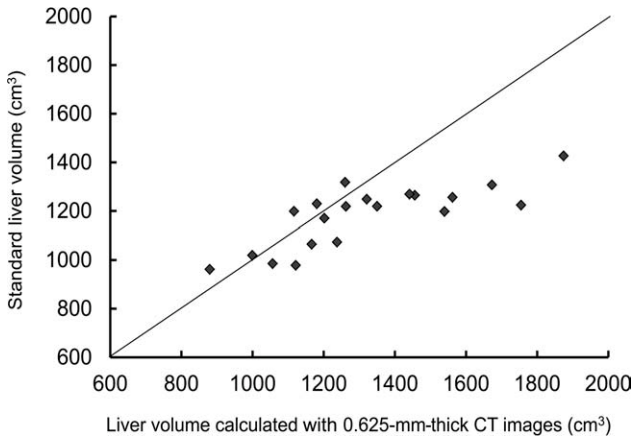

Figure 5. Scatter plots of whole liver volumes estimated from 0.625-mm images versus standard liver volumes calculated from the body surface area.

different volume calculations would be with 3D data. This prompted us to conduct this study, which is the first detailed report in which the effects of the slice thickness [ranging from 0.625 mm (ie, isotropic 3D data) to 10 mm] on the calculated liver volume have been quantitatively evaluated. The liver volumes calculated on the basis of CT volumetry increased as the slice thickness decreased, probably because of reduced errors from partial volume effects. Although some previous research on CT and magnetic resonance organ volumetry showed similar tendencies,[11,18-20] isotropic 3D image data were not included in those studies. Our data could be useful for estimating and improving the accuracy of CT liver volumetry.

The maximum differences in the volumes calculated from 0.625-mm-thick and thicker images were estimated with the 95% limits of agreement (Table 4): −17.8 cm^3 (−1.29%) for 2.5-mm images, −26.8 cm^3 (−2.22%) for 5-mm images, and −78.0 cm^3 (−6.18%) for 10-mm images for whole livers; −10.6 cm^3 (−1.19%) for 2.5-mm images, −25.3 cm^3 (−2.98%) for 5-mm images, and −50.2 cm^3 (−5.97%) for 10-mm images for right lobes; −11.2 cm^3 (−2.40%) for 2.5-mm images, −17.3 cm^3 (−4.09%) for 5-mm images, and −43.3 cm^3 (−9.92%) for 10-mm images for left lobes; and −9.2 cm^3 (−3.81%) for 2.5-mm images, −10.9 cm^3 (−4.63%) for 5-mm images, and −35.6 cm^3 (−15.1%) for 10-mm images for lateral segments. These values agree with our rough estimates based on the numerical simulation. The percentages were larger for partial livers versus whole livers. This suggests that the effects of the slice thickness on volume calculations are larger for smaller objects. For lateral segments (ie, the smallest grafts), the percentage was approximately −5%. According to our results, if a maximum error of 5% in the graft volume is acceptable and will not have a clinical impact, 5-mm-thick images are acceptable for CT liver volumetry, and 0.625-mm 3D images are not required. In contrast, if an error of 5% in the graft volume is unacceptable, 3D data could be essential for CT volumetry.

Reported results for the accuracy of CT liver volumetry show deviations from the reference standard that range from 0% to more than 30%,[6-10] although none of these results were based on CT liver volumetry with 3D image data. Nakayama et al.[9] reported that the mean liver volume calculated with liquid-displacement measurements after the surgical operation was larger than the volume calculated by preoperative manual CT volumetry by only 2.4% for liver recipients who underwent living liver transplantation. Our data suggest that this small degree of error might be explained by the effect of the slice thickness to some extent because Nakayama et al. used 5-mm images in their study. On the other hand, Lemke et al.[10] reported that the mean liver volume calculated during the surgical operation was 34% smaller than the volume calculated by preoperative CT volumetry for living donor right liver lobes with 7.5-mm images. Our data suggest that the large degree of error reported by Lemke et al. cannot be explained by the effects of the slice thickness. A number of causes for errors, such as the imaging technique and partial volume effects, the hepatic physical density, the exact contour and segment recognition, the intraoperative drainage of liquids from the liver, and hepatic volume deviations, have been suggested.[10] The difference between the assumed liver cutting line before the operation and the actual cutting line in donor liver resection is another of the various potential causes for errors. Lemke et al. speculated that the influence of perfusion on the liver volume could account for the large discrepancy that they reported. Meanwhile, in association with advanced cirrhosis, the portal venous flow, which is the predominant source of blood volume to the liver, is often reduced. Therefore, the pathological variations in size and weight from in vivo to in vitro would be lessened with greater degrees of portal hypertension. This could cause the small discrepancies reported in Nakayama et al.'s study, in which most subjects had cirrhotic livers. The relative significance of the various potential factors that could cause measurement errors in CT liver volumetry could depend on the degree of liver disease.

Because 3D images have lower partial volume effects, it would be reasonable for volumes calculated from 0.625-mm 3D images to be more precise than volumes from 5-mm images. However, more time and effort are required with 0.625-mm 3D images versus 5-mm images because the number of 0.625-mm 3D images is 8 times greater than the number of 5-mm images. In other words, it could potentially take 8 times longer to draw the boundaries. In fact, the average time required for completing the manual correction was 98 minutes for 0.625-mm 3D images in this study, whereas the processing time for manual segmentation is usually 20 to 50 minutes for 5-mm images.[9,14] Therefore, radiologists and surgeons should try to achieve a good balance between accuracy and workload. The knowledge derived from this study could be helpful in determining the optimal slice thickness for clinical practice.

Because the widths of the 95% limits of agreement for the calculated liver volumes were narrow (ie, 1.18% on 2.5-mm images, 2.58% on 5-mm images, and 3.96% on 10-mm images for whole livers), we might be able to estimate liver volumes with greater accuracy from thicker images if we compensated the calculated values with the mean volume differences, as some researchers have proposed.[10,20-22] However, because the mean differences between the calculated volumes from 3D images and thicker images could depend on many factors (eg, CT scanners, reconstruction algorithms, and window settings), further investigations are needed before this compensation technique can be employed.

Some researchers have reported that actual liver volumes are smaller than those calculated with CT volumetry.[7,10,22] This phenomenon has been explained by the effects of physiological perfusion on the liver volume or the intraoperative drainage of liquids from the liver. On the other hand, our results showed that liver volumes calculated from 0.625-mm 3D images were significantly larger than volumes from thicker images. Therefore, it is possible that liver volumes calculated from 3D images could show a larger degree of error than volumes from thicker images. If 3D images are going to be used for CT liver volumetry, this possible paradoxical effect should be kept in mind.

This study has several limitations. First, no surgical specimens were obtained for direct comparisons. However, because the purpose of this study was to evaluate the relationship between the slice thickness and the calculated volume in CT liver volumetry, we were afraid that comparisons between calculated volumes and surgically evaluated volumes would make things more complicated. Second, only 1 radiologist was involved in CT liver volumetry. However, because the interobserver variation for CT volumetry is considered to be small,[23] we believe that this was unlikely to have been a substantial limitation.

In conclusion, the liver volume calculated with CT volumetry significantly increases as the slice thickness decreases. With current technologies, this has potential implications for the work load of radiologists and surgeons. If a maximum error of 5% in the calculated graft volume will not have a significant clinical impact, 5-mm-thick images are acceptable for CT liver volumetry. However, if an error of 5% is unacceptable, 3D data could be essential for CT volumetry.

ACKNOWLEDGMENTS

The authors thank Mr. Adam Starkey for his efforts in developing the software tools used in this research.

REFERENCES

1. Heymsfield SB, Fulenwider T, Nordlinger B, Barlow R, Sones P, Kutner M. Accurate measurement of liver, kidney, and spleen volume and mass by computerized axial tomography. Ann Intern Med 1979;90:185-187.
2. Kawasaki S, Makuuchi M, Matsunami H, Hashikura Y, Ikegami T, Chisuwa H, et al. Preoperative measurement of segmental liver volume of donors for living related liver transplantation. Hepatology 1993;18:1115-1120.
3. Wang F, Pan KT, Chu SY, Chan KM, Chou HS, Wu TJ, Lee WC. Preoperative estimation of the liver graft weight in adult right lobe living donor liver transplantation using maximal portal vein diameters. Liver Transpl 2011;17:373-380.
4. Soejima Y, Shimada M, Suehiro T, Hiroshige S, Ninomiya M, Shiotani S, et al. Outcome analysis in adult-to-adult living donor liver transplantation using the left lobe. Liver Transpl 2003;9:581-586.
5. Taner CB, Dayangac M, Akin B, Balci D, Uraz S, Duran C, et al. Donor safety and remnant liver volume in living donor liver transplantation. Liver Transpl 2008;14: 1174-1179.
6. Sakamoto S, Uemoto S, Uryuhara K, Kim Id, Kiuchi T, Egawa H, et al. Graft size assessment and analysis of donors for living donor liver transplantation using right lobe. Transplantation 2001;71:1407-1413.
7. Hiroshige S, Shimada M, Harada N, Shiotani S, Ninomiya M, Minagawa R, et al. Accurate preoperative estimation of liver-graft volumetry using three-dimensional computed tomography. Transplantation 2003;75: 1561-1564.
8. Frericks BB, Caldarone FC, Nashan B, Savellano DH, Stamm G, Kirchhoff TD, et al. 3D CT modeling of hepatic vessel architecture and volume calculation in living donated liver transplantation. Eur Radiol 2004;14:326-333.
9. Nakayama Y, Li Q, Katsuragawa S, Ikeda R, Hiai Y, Awai K, et al. Automated hepatic volumetry for living related liver transplantation at multisection CT. Radiology 2006; 240:743-748.
10. Lemke AJ, Brinkmann MJ, Schott T, Niehues SM, Settmacher U, Neuhaus P, Felix R. Living donor right liver lobes: preoperative CT volumetric measurement for calculation of intraoperative weight and volume. Radiology 2006;240:736-742.
11. Reiner CS, Karlo C, Petrowsky H, Marincek B, Weishaupt D, Frauenfelder T. Preoperative liver volumetry: how does the slice thickness influence the multidetector computed tomography- and magnetic resonance-liver volume measurements? J Comput Assist Tomogr 2009;33:390-397.
12. Urata K, Kawasaki S, Matsunami H, Hashikura Y, Ikegami T, Ishizone S, et al. Calculation of child and adult standard liver volume for liver transplantation. Hepatology 1995;21:1317-1321.
13. Sethian JA. Level Set Methods and Fast Marching Methods: Evolving Interfaces in Computational Geometry, Fluid Mechanics, Computer Vision and Materials Science. Cambridge, United Kingdom: Cambridge University Press; 1999.
14. Suzuki K, Kohlbrenner R, Epstein ML, Obajuluwa AM, Xu J, Hori M. Computer-aided measurement of liver volumes in CT by means of geodesic active contour segmentation coupled with level-set algorithms. Med Phys 2010; 37:2159-2166.
15. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1:307-310.
16. Bland JM, Altman DG. Measuring agreement in method comparison studies. Stat Methods Med Res 1999;8: 135-160.
17. Kiuchi T, Kasahara M, Uryuhara K, Inomata Y, Uemoto S, Asonuma K, et al. Impact of graft size mismatching on graft prognosis in liver transplantation from living donors. Transplantation 1999;67:321-327.
18. Berthelet E, Liu M, Truong P, Czaykowski P, Kalach N, Yu C, et al. CT slice index and thickness: impact on organ contouring in radiation treatment planning

for prostate cancer. J Appl Clin Med Phys 2003;4: 365-373.

19. Hermoye L, Laamari-Azjal I, Cao Z, Annet L, Lerut J, Dawant BM, Van Beers BE. Liver segmentation in living liver transplant donors: comparison of semiautomatic and manual methods. Radiology 2005;234:171-178.
20. Emirzeoglu M, Sahin B, Selcuk MB, Kaplan S. The effects of section thickness on the estimation of liver volume by the Cavalieri principle using computed tomography images. Eur J Radiol 2005;56:391-397.
21. Karlo C, Reiner CS, Stolzmann P, Breitenstein S, Marincek B, Weishaupt D, Frauenfelder T. CT- and MRI-based volumetry of resected liver specimen: comparison to intraoperative volume and weight measurements and calculation of conversion factors. Eur J Radiol 2010;75: e107-e111.
22. Yoneyama T, Asonuma K, Okajima H, Lee KJ, Yamamoto H, Takeichi T, et al. Coefficient factor for graft weight estimation from preoperative computed tomography volumetry in living donor liver transplantation. Liver Transpl 2011;17:369-372.
23. Sandrasegaran K, Kwo PW, DiGirolamo D, Stockberger SM Jr, Cummings OW, Kopecky KK. Measurement of liver volume using spiral CT and the curved line and cubic spline algorithms: reproducibility and interobserver variation. Abdom Imaging 1999;24:61-65.