ORIGINAL ARTICLE

Preoperative Estimation of the Liver Graft Weight in Adult Right Lobe Living Donor Liver Transplantation Using Maximal Portal Vein Diameters

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An accurate preoperative estimate of the graft weight is vital to avoid small-for-size syndrome in the recipient and ensure donor safety after adult living donor liver transplantation (LDLT). Here we describe a simple method for estimating the graft volume (GV) that uses the maximal right portal vein diameter (RPVD) and the maximal left portal vein diameter (LPVD). Between June 2004 and December 2009, 175 consecutive donors undergoing right hepatectomy for LDLT were retrospectively reviewed. The GV was determined with 3 estimation methods: (1) the radiological graft volume (RGV) estimated by computed tomography (CT) volumetry; (2) the computed tomography–calculated graft volume (CGV-CT), which was obtained by the multiplication of the standard liver volume (SLV) by the RGV percentage with respect to the total liver volume derived from CT; and (3) the portal vein diameter ratio–calculated graft volume (CGV-PVDR), which was obtained by the multiplication of the SLV by the portal vein diameter ratio [PVDR; ie, PVDR = $RPVD^2/(RPVD^2 + LPVD^2)$]. These values were compared to the actual graft weight (AGW), which was measured intraoperatively. The mean AGW was 633.63 ± 107.51 g, whereas the mean RGV, CGV-CT, and CGV-PVDR values were 747.83 ± 138.59, 698.21 ± 94.81, and 685.20 ± 90.88 cm^3, respectively. All 3 estimation methods tended to overestimate the AGW ($P < 0.001$). The actual graft-to-recipient body weight ratio (GRWR) was 1.00% ± 0.19%, and the GRWRs calculated on the basis of the RGV, CGV-CT, and CGV-PVDR values were 1.19% ± 0.25%, 1.11% ± 0.22%, and 1.09% ± 0.21%, respectively. Overall, the CGV-PVDR values better correlated with the AGW and GRWR values according to Lin's concordance correlation coefficient and the Landis and Kock benchmark. In conclusion, the PVDR method is a simple estimation method that accurately predicts GVs and GRWRs in adult LDLT. ***Liver Transpl 17:373–380, 2011.*** **© 2011 AASLD.**

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Since the first report in 1994,[1] adult living donor liver transplantation (LDLT) has increasingly been accepted as an important therapeutic option in the management of end-stage liver failure because of the shortage of deceased liver donors. The key factor critical to the success of LDLT is the adequacy of the graft mass in providing sufficient metabolic and synthetic capacity and ensuring donor safety.[2-4] The use

Abbreviations: 2D, 2-dimensional; AGW, actual graft weight; BSA, body surface area; CCC, concordance correlation coefficient; CGV-CT, computed tomography–calculated graft volume; CGV-PVDR, portal vein diameter ratio–calculated graft volume; CT, computed tomography; GRWR, graft-to-recipient body weight ratio; GRWR-CT, computed tomography–calculated graft-to-recipient body weight ratio; GRWR-PVDR, portal vein diameter ratio–calculated graft-to-recipient body weight ratio; GRWR-RGV; radiological graft volume–calculated graft-to-recipient body weight ratio; GV, graft volume; LDLT, living donor liver transplantation; LPVD, left portal vein diameter; MHV, middle hepatic vein; MRI, magnetic resonance imaging; PVDR, portal vein diameter ratio; RGV, radiological graft volume; RPVD, right portal vein diameter; SLV, standard liver volume.

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of small-for-size grafts with graft-to-recipient body weight ratios (GRWRs) less than 0.8% to 1% has been associated with reduced graft survival[2,5,6] because of portal hyperperfusion leading to parenchymal cell injury. An accurate preoperative estimate of the graft weight is, therefore, crucial for avoiding small-for-size syndrome in the recipient and for preventing postoperative hepatic failure in the donor after LDLT.

Currently, computed tomography (CT) and magnetic resonance imaging (MRI) are used by many liver transplantation programs worldwide as the gold standards for the preoperative assessment of the graft volume (GV) in potential living donors. Despite recent advances, these radiological volumetric techniques can be expensive and time-consuming, and they are associated with error ratios of 5% to 36% in comparison with the intraoperatively measured actual graft weight (AGW).[2,7-10] In this article, we describe a simple method for estimating the GV/weight values that uses the maximal right portal vein diameter (RPVD) and the maximal left portal vein diameter (LPVD), and we compare its accuracy to that of 2-dimensional (2D) CT volumetry.

PATIENTS AND METHODS

Patients

Between June 2004 and December 2009, 175 consecutive healthy donors undergoing right lobe hepatectomy for adult LDLT at the Division of Liver and Transplantation Surgery (Chang Gung Memorial Hospital Linkou Medical Center) were retrospectively reviewed. For all donors, the liver graft and remnant liver volumes were adequate; this was determined by preoperative helical CT.

Surgical Technique

Living donor right lobe hepatectomy was routinely performed by the senior surgeon (W.C.L.) of the unit. Briefly, the liver was exposed via a right subcostal abdominal incision with a midline extension to the xiphisternum. Hilar dissection was undertaken to isolate the right hepatic artery after cholecystectomy. The right hemiliver was then completely mobilized from the posterior abdominal wall and the retrohepatic inferior vena cava. The right hepatic vein was then looped. Parenchymal transection was performed with an ultrasonic dissector along a line to the right of middle hepatic vein (MHV). The MHV was routinely preserved for the donor. Once the parenchymal transection was completed, the right hepatic artery, portal vein, and hepatic vein were sequentially clamped and divided. The procured graft was flushed via the right portal vein on the back table with histidine-tryptophan-ketoglutarate solution, and the AGW was measured. Any tributary hepatic veins of segments V and VIII that were 5 mm or larger in diameter were reconstructed with interposition vascular grafts (cryopreserved iliac arteries or veins from deceased donors) before their implantation into the recipients.

2D CT Volumetry Protocol

Preoperative multidetector CT images were obtained with a Somatom Sensation 16 CT scanner (Siemens AG, Berlin, Germany) with a 1-mm slice thickness and triple-phase intravenous contrast enhancement. The scanning parameters were as follows: 120 kV, 200 effective mAs, 0.75×16 mm^2 collimation, a rotation time of 0.5 seconds, and a table speed of 9 mm per rotation with image reconstruction increments of 5 mm. The axial hepatic venous phase was used for CT volumetry measurements of the donor liver. For the measurement of the right lobe GV, the virtual hepatectomy plan was defined along the Cantlie line with preservation of the MHV for the donor. The perimeters of the liver and the graft were outlined by hand tracing on each slice by 2 radiologists (K.T.P. and S.Y.C.), and the enclosed area was calculated with image analysis software (Somaris/5 VB 10B, Siemens AG). The Hounsfield units were set from 25 to 300. The liver volume was then obtained as the sum of all areas from the intervals of the serial CT slices. Reconstructed CT portography was used to measure the maximal portal vein diameter. The oblique, coronal, and sagittal views of the reconstructed images were used to measure the portal vein diameters. The RPVD and LPVD were estimated at the main portal vein bifurcation, and the maximal portal vein diameters were chosen to calculate the GV.

GV Measurements

The radiological graft volume (RGV; cm^3) was the volume of the donor's right lobe directly measured by 2D CT volumetry. The RGV percentage with respect to the total donor liver volume was also estimated with CT volumetry. The standard liver volume (SLV) was calculated with Urata et al.'s formula[11]:

$$\mathrm{SLV\,(cm^3)} = 706.2 \times \mathrm{BSA\,(m^2)} + 2.4$$

where BSA is the body surface area. Mosteller's formula[12] was adopted for BSA:

$$\mathrm{BSA} = \sqrt{[\mathrm{Weight\,(kg)} \times \mathrm{Height\,(cm)}/3600]}$$

The computed tomography–calculated graft volume (CGV-CT) was obtained by the multiplication of the SLV by the RGV percentage. The portal vein diameter ratio (PVDR) was calculated with the maximal RPVD and LPVD values (mm) on CT as follows:

$$\mathrm{PVDR} = \mathrm{RPVD}^2/(\mathrm{RPVD}^2 + \mathrm{LPVD}^2)$$

The ratio was derived under the assumption that the percentage of the right lobe of the liver is determined by the distribution of the blood flow in the right and left portal veins and thus by the cross-sectional area of the respective veins [π(maximal diameter/2)^2, where the maximal diameter is measured in

millimeters]. The portal vein diameter ratio–calculated graft volume (CGV-PVDR) was, therefore, obtained by the multiplication of the SLV by the PVDR. Under the assumption that the parenchymal density of the normal liver was 1 g/mL,[11] the estimated liver graft weight was almost equal to the calculated liver GV. The GRWR was calculated with the AGW value and with each of these estimates of the graft weight. The error ratio was expressed as follows[2]:

$$\text{Error ratio}\,(\%) = [\text{Estimated GV}\,(\text{cm}^3) - \text{AGW}\,(\text{g})]/\text{AGW}\,(\text{g}) \times 100$$

An error ratio less than 20% was considered to indicate an acceptable AGW estimate.[3]

TABLE 1. Donor Demographics and Perioperative Characteristics

	Study Group (n = 175)
Age (years)	31.34 ± 8.25
Gender: male/female (n/n)	96/79
Height (cm)	166.30 ± 8.88
Weight (kg)	62.63 ± 10.20
Body mass index (kg/m^2)	22.58 ± 2.80
BSA (m^2)	1.70 ± 0.17
SLV (cm^3)	1200.84 ± 118.46
Duration of operation (minutes)	377.94 ± 55.44
Intraoperative blood loss (mL)	142.76 ± 93.64
Length of hospitalization (days)	9.13 ± 2.95
Morbidity (n)	1 (bile leak)
Mortality (n)	0

NOTE: The values are means and standard deviations unless noted otherwise.

Statistical Analysis

The continuous data are expressed as means and standard deviations. Proportions are presented as numbers and percentages. Statistical analysis was performed with the Student *t* test or analysis of variance test for continuous data, and Pearson's χ^2 test was used for proportions. *P* values less than 0.05 were considered to be statistically significant. Simple linear regression analyses were performed to evaluate the correlation between the AGW and GRWR values and the 3 GV estimation methods. In addition, Lin's concordance correlation coefficient (CCC)[13,14] was used to measure the agreement between different estimation techniques. The Landis and Koch benchmark[15] was used to determine the degree of agreement as follows: poor agreement (0.00), slight agreement (0.01-0.20), fair agreement (0.21-0.40), moderate agreement (0.41-0.60), substantial agreement (0.61-0.80), and almost perfect agreement (0.81-1.00). All statistical analyses were performed with SPSS, version 13.0 (SPSS, Inc., Chicago, IL).

RESULTS

Descriptive Statistics

The donor demographics and perioperative parameters are summarized in Table 1. The mean AGW was 633.63 ± 107.51 g (Table 2). The mean percentage of the right lobe GV with respect to the donor's total liver volume as estimated by CT was 58.13% ± 5.16%, and the GV mean percentage as estimated by the PVDR method was 57.03% ± 4.38%. Both were significantly different ($P = 0.001$) according to the paired *t* test. In comparison with the AGW, the graft weight was overestimated by all 3 methods that we studied ($P < 0.001$). In comparison with the RGV and CGV-CT methods, the CGV-PVDR method produced graft weight estimates closest to the AGW values. The error ratio of the RGV graft weight estimate (18.56% ± 14.55%) was statistically significantly higher than the CGV-CT and CGV-PVDR error ratios ($P < 0.001$ and <

TABLE 2. Comparison of the Right Lobe Graft Weight/GV Ratios, GRWRs, Error Ratios, and Accuracy With the Three Estimation Methods

	AGW	RGV	CGV-CT	CGV-PVDR	*P* Value
Graft weight (g) or GV (cm^3)	633.63 ± 107.51	747.83 ± 138.59	698.21 ± 94.81	685.20 ± 90.88	<0.001
GRWR (%)	1.00 ± 0.19	1.19 ± 0.25	1.11 ± 0.22	1.09 ± 0.21	<0.001
Error ratio (%)		18.56 ± 14.55	11.71 ± 15.04	9.46 ± 12.82	<0.001
Accuracy [n/N (%)]*		94/175 (53.7)	124/175 (70.9)	141/175 (80.6)	<0.001
Adjusted GV (cm^3)†		633.32 ± 82.46	633.41 ± 63.90	634.00 ± 76.37	0.996
Adjusted GRWR (%)†		1.01 ± 0.19	1.01 ± 0.19	1.01 ± 0.19	0.988
Adjusted error ratio (%)†		1.07 ± 10.93	1.68 ± 13.13	1.42 ± 11.80	0.894
Adjusted accuracy [n/N (%)]*,†		163/175 (93.1)	155/175 (88.6)	157/175 (89.7)	0.317

NOTE: The values are means and standard deviations unless noted otherwise.
*The accuracy values are presented as n/N, where n is the number of cases meeting the clinically acceptable variation and N is the number of all cases with AGWs (the error ratio was within ±20%). Percentages are shown within parentheses.
†The values were adjusted with the regression equation.

0.001, respectively). Even though the CGV-PVDR method had the smallest error ratio (9.46% ± 12.82%), the difference between this estimation method and the CGV-CT method (11.71% ± 15.04%) was not statistically significant ($P = 0.334$). The accuracy of the CGV-PVDR method was 80.6%, which was higher than the accuracy of the CGV-CT and RGV methods (70.9% and 53.7%, respectively, $P < 0.001$).

The mean actual GRWR was 1.00% ± 0.19%, which was significantly different from the other 3 estimates ($P < 0.001$). Although there were no statistically significant differences between the computed tomography–calculated graft-to-recipient body weight ratio (GRWR-CT; 1.11% ± 0.22%) and the portal vein diameter ratio–calculated graft-to-recipient body weight ratio (GRWR-PVDR; 1.09% ± 0.21%, $P = 0.837$), the values of these 2 groups did differ significantly from the radiological graft volume–calculated graft-to-recipient body weight ratio (GRWR-RGV; 1.19% ± 0.25%, $P = 0.022$ and $P = 0.001$, respectively). Once again, the GRWR-PVDR was closest to the actual GRWR in comparison with the values from the other 2 estimation methods.

Simple Linear Regression Model

The correlations between the AGW and the 3 methods of GV estimation were linear (Fig. 1A-C), and the corresponding R^2 values were 0.589 for RGV ($P < 0.001$), 0.354 for CGV-CT ($P < 0.001$), and 0.504 for CGV-PVDR ($P < 0.001$). The correlation between the actual GRWR and the 3 methods of GRWR estimation were also linear (Fig. 1D-F), and the corresponding R^2 values were 0.693 for the GRWR-RGV method ($P < 0.001$), 0.579 for the GRWR-CT method ($P < 0.001$), and 0.651 for the GRWR-PVDR method ($P < 0.001$). The details of the regression models comparing the RGV, CGV-CT, and CGV-PVDR values to the AGW and GRWR values are summarized in Table 3. Once they were corrected by the regression equation, the adjusted RGV, CGV-CT, and CGV-PVDR values became homogeneous and demonstrated no statistically significant differences with respect to the GVs, GRWRs, error ratios, or accuracy rates (Table 2).

CCC

Lin's CCC was 0.52 between AGW and RGV, 0.49 between AGW and CGV-CT, and 0.62 between AGW and CGV-PVDR. Two scatter plots showed that most values were lying above the 45-degree line of agreement, and this indicated an overestimation of the GV values by the RGV and CGV-CT methods (Fig. 2A,B). However, the CGV-PVDR–AGW scatter plot demonstrated values that were gathered around the 45-degree line of agreement, and this indicated good agreement (Fig. 2C). According to the Landis and Koch benchmark, there was substantial agreement between the CGV-PVDR and AGW values, whereas there was moderate agreement between the RGV and CGV-CT values and the AGW values. The values of Lin's CCC between the actual GRWRs and the GRWR-RGV, GRWR-CT, and GRWR-PVDR values were 0.6, 0.66, and 0.74, respectively (Fig. 2D-F); this suggested that the GRWR-PVDR values and, to a lesser extent, the GRWR-CT values had better concordance with the actual GRWR values than the GRWR-RGV values.

DISCUSSION

This study shows that the PVDR method can be used to accurately estimate right lobe GV/weight values when potential donors are being evaluated preoperatively for adult LDLT. The PVDR method can also be employed to predict the percentage of the right lobe graft with respect to the total donor liver volume. The rationale for using the PVDR method was initially based on the observation that the sizes of the right and left portal veins seem to reflect the differential hepatic masses of the 2 liver lobes clinically and radiologically. Although no available studies have specifically investigated the anatomical differences in the sizes of the right and left portal veins and their relationship to the proportions of the corresponding hepatic lobes, we can intuitively surmise that the sizes of the 2 liver lobes parallel the volume of the blood flow and hepatotrophic factors in the 2 portal veins. The sizes of the 2 portal veins and their blood flow should also be proportional to the metabolic and nutritional demands of the liver lobes. This hypothesis is indirectly supported by some earlier animal studies by Child et al.,[16] Sgro et al.,[17] and Takeshige et al.,[18] who suggested that the volume of the portal blood flow is the most important factor for liver regeneration.

An accurate preoperative estimate of the liver GV is essential for the selection of the appropriate donor for optimal recipient outcomes after LDLT. The minimum graft size required for LDLT to provide adequate functional hepatic mass has been reported to be 30% to 40% of the recipient's weight[5,19,20] (or GRWR = 0.8%-1.0%[21,22]). On the other hand, the donor liver remnant must be greater than 30% of the original liver to ensure donor safety and prevent postoperative hepatic insufficiency.[7,23] The advances in noninvasive, radiological volumetric techniques (CT and MRI) have simplified the process of donor evaluation.[4] However, preoperative estimates of graft and remnant liver volumes by CT/MRI remain inaccurate and are often associated with underestimation or, more importantly, overestimation errors,[2,7-10,23,24] as observed in this study.

Many factors could potentially result in inaccuracy with radiological volumetric techniques. One source of inaccuracy could be the presence of blood in the liver vasculature during CT/MRI scanning and intraoperative weighing of the nonperfused graft.[2,9,25] Frericks et al.[26] demonstrated an approximately 33% difference in the total liver volume before and after fluid infusion in a porcine model. Another factor contributing to the estimation error could be the discrepancy between the simulated preoperative partitioning and

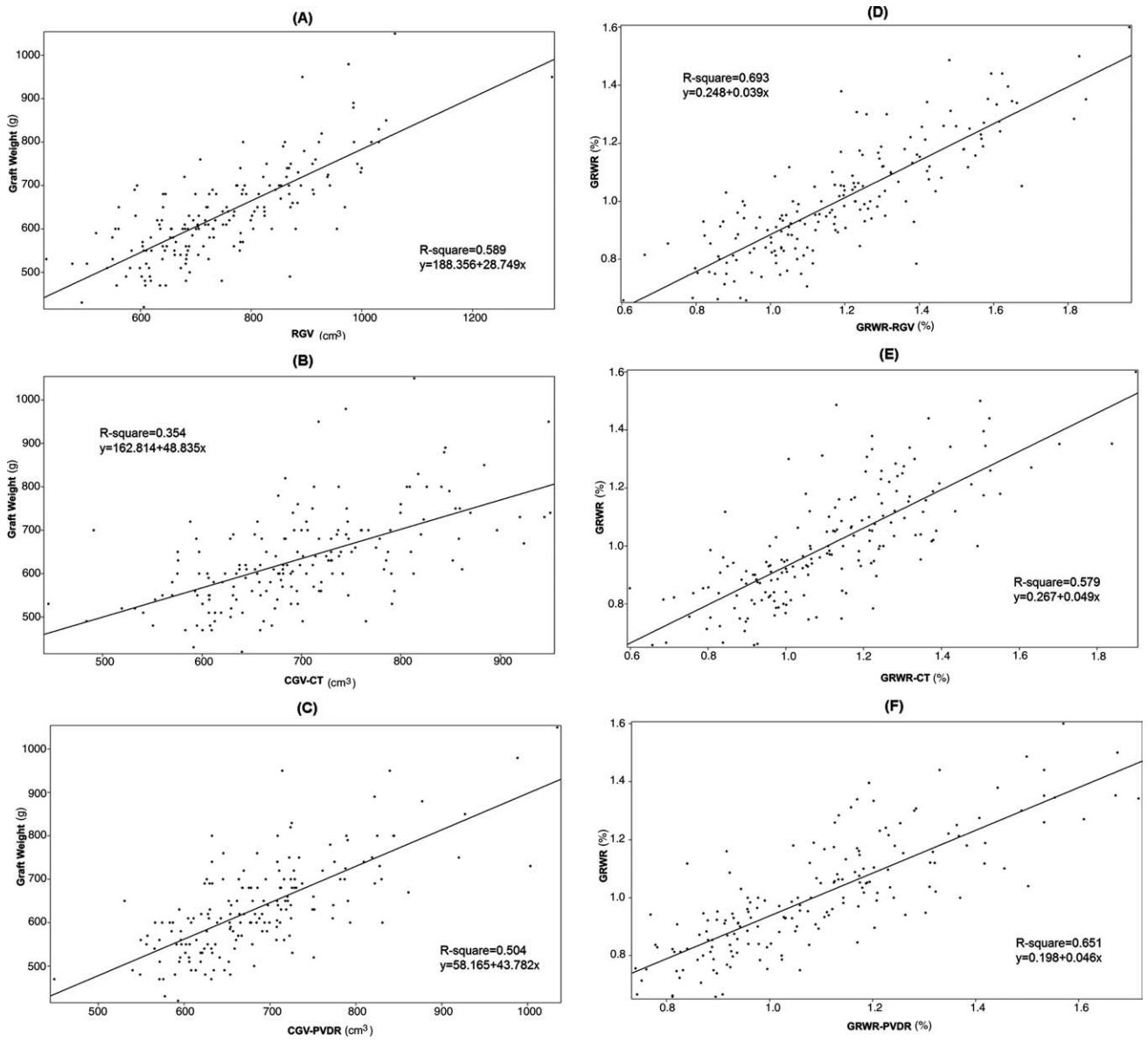

Figure 1. Correlations between estimated GVs and AGWs [(A) RGV, (B) CGV-CT, and (C) CGV-PVDR] and between estimated GRWRs and actual GRWRs [(D) GRWR-RGV, (E) GRWR-CT, and (F) GRWR-PVDR] for 175 living liver donors by the linear regression model.

TABLE 3. Simple Linear Regression Models Correlating RGV, CGV-CT, and CGV-PVDR to AGW

	Coefficient	Standard Error	Low	High	*P* Value	R^2 Value	Adjusted R^2 Value	Cross-Validation R^2 Value*
RGV	0.595	0.039	0.521	0.670	<0.001	0.589	0.587	0.577
CGV-CT	0.674	0.069	0.538	0.811	<0.001	0.354	0.350	0.337
CGV-PVDR	0.840	0.063	0.715	0.965	<0.001	0.504	0.501	0.489
GRWR-RGV	0.638	0.032	0.574	0.701	<0.001	0.693	0.691	0.686
GRWR-CT	0.662	0.043	0.577	0.746	<0.001	0.579	0.577	0.570
GRWR-PVDR	0.738	0.041	0.657	0.820	<0.001	0.651	0.649	0.642

*Cross-validation was performed with the bootstrapping method for inferences of bias.

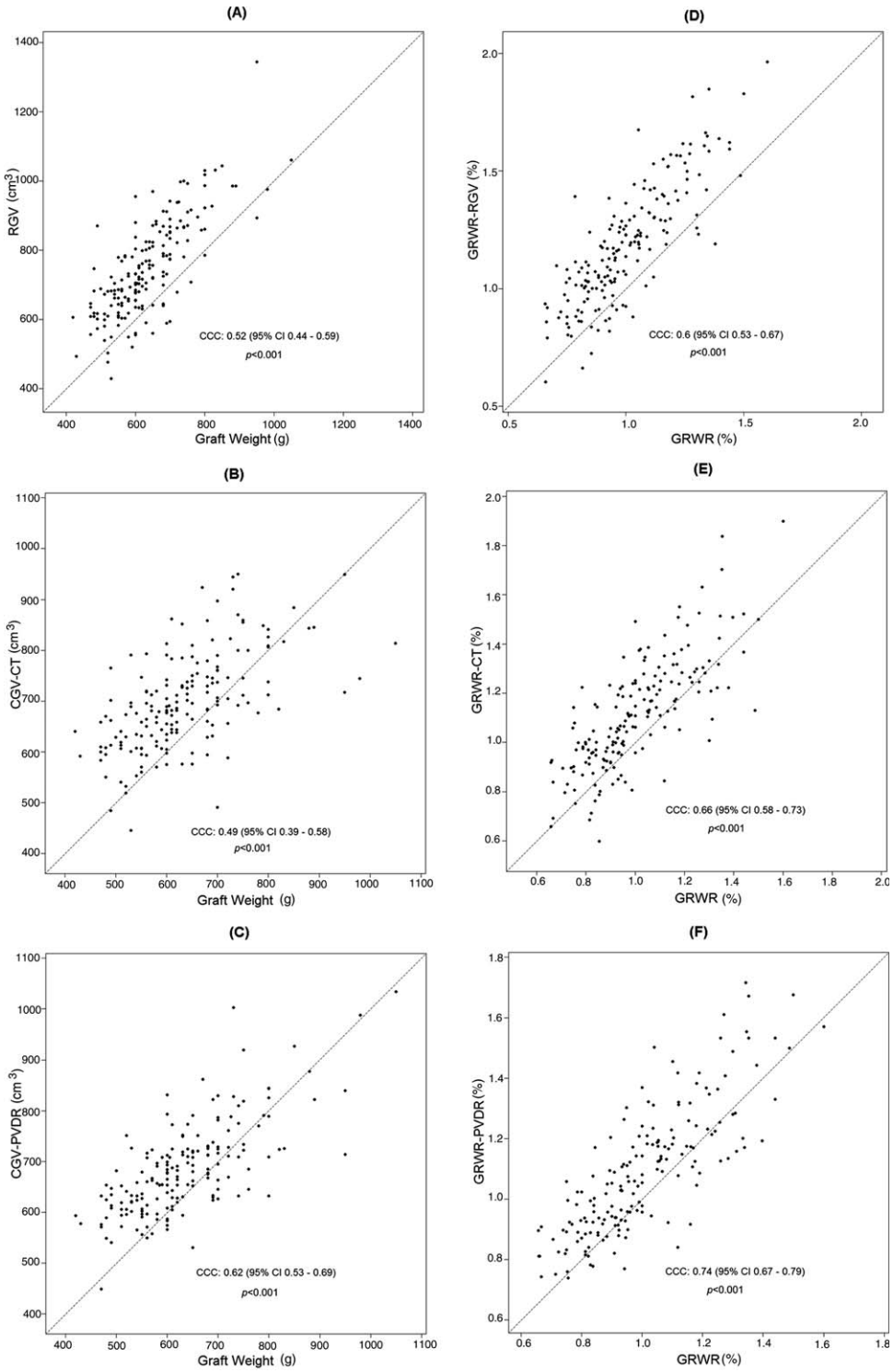

Figure 2. CCCs between estimated GVs and AGWs [(A) RGV, (B) CGV-CT, and (C) CGV-PVDR] and between estimated GRWRs and actual GRWRs [(D) GRWR-RGV, (E) GRWR-CT, and (F) GRWR-PVDR].

the actual plane of the intraoperative parenchymal transection. Marcos et al.[27] reported that a difference of 2 cm could result in a graft weight difference as high as 200 g. The variation in the liver density is another potential source of error: Lemke et al.[28] reported that the conversion factor was approximately 12% higher than the expected value of 1 g/mL with a mean density of 1.1172 g/mL in 16 transplanted liver lobes. On the other hand, Yoneyama et al.[29] showed that although the specific gravity of a cirrhotic liver

was 1.01 g/mL, the correlation coefficient between the CT-estimated graft weight and the AGW decreased to 0.85 in a noncirrhotic liver. The dehydrating effect of the high osmotic pressure of University of Wisconsin solution is another reason commonly cited for the observed inaccuracies[7,23,25,30]; a reduction of approximately 4% in the graft weight 15 minutes after flushing has been reported.[2] Kayashima et al.[7] also noted that grafts from younger donors are more influenced by dehydration due to University of Wisconsin solution. Age can also affect graft compliance[31]: in their series, Yonemura et al.[25] observed significant GV overestimation in donors less than 30 years old versus donors more than 30 years old.

In an effort to better evaluate the GV preoperatively, Salvalaggio et al.[10] reported formula-derived GV estimates, and Gondolesi et al.[3] used the fixed value of 57% for right lobe prediction. Although these formulas that are based on fixed calculated percentages of the right lobe GV have acceptable correlation coefficients and lower error ratios in comparison with radiological volume estimation, they have not addressed the issue of variations in the percentage of the right lobe with respect to the whole liver,[32] with the mean right lobe GV ranging from 56% to 65%.[3,8,10,32,33] We examined the utility of RPVD and LPVD values in providing an easier method of estimating the right lobe GV percentage to overcome its marked variations in the population. The maximal portal vein diameters can be readily measured by preoperative CT or Doppler ultrasonography without the need for more expensive, labor-intensive, and time-consuming CT volumetry. The accuracy of the PVDR method in estimating GV has been illustrated in this study by its lower error ratio, higher accuracy rate, and better approximation with respect to the actual GRWR in comparison with either the CGV-CT method or the RGV method.

Although Pearson's correlation coefficient and the adjusted R^2 value are commonly used to quantify the strength of association between 2 observations in a simple regression model, the validity of the equation is limited to a linear relationship, and its sensitivity is affected by outliers and extreme values.[34] Lin's CCC, on the other hand, is considered the most appropriate method for evaluating equivalence between alternative methods for continuous data.[35,36] Lin's CCC contains both a measure of precision (represented by Pearson's correlation coefficient) and a bias correction factor that measures deviations from the 45-degree line through the origin (ie, a measure of accuracy).[13,14] As demonstrated in this study, even though the adjusted R^2 value was slightly better with the RGV method, the GVs, GRWRs, error ratios, and accuracy rates were not statistically different across the 3 estimation methods once they were corrected with the regression equations. The agreement between the actual GV/GRWR values and the PVDR values was better shown by Lin's CCC than the simple linear regression.

The main disadvantage of this formula in comparison with CT volumetry is its inability to estimate the volumes of segments V and VIII. Anterior section congestion may jeopardize graft function in right lobe LDLT when the MHV is preserved for donor safety. Adequate drainage of these 2 segments is particularly important when the GV is marginal. In order to prevent congestion in segments V and VIII of the graft after reperfusion, we routinely re-anastomose any significant tributaries from these segments on the back table to the right hepatic vein or the inferior vena cava with cryopreserved interposition vascular grafts from previously deceased donors.

Because the PVDR can accurately reflect the percentage of the right lobe liver graft, this formula could be easily applied as part of an initial donor screening process in order to minimize unnecessary donor investigations and procedures. It could also be a useful guide to the selection of potential donors for a newly established liver transplantation unit with limited experience in accurately measuring GVs. Another advantage of using the PVDR method rather than CT volumetry in evaluating GVs can be found in split liver transplantation: CT of the liver might not be available or logistically feasible before organ procurement. In such a situation, a rapid GV assessment could be performed with the PVDR obtained from the preoperative ultrasound examination. Our unit recently reported its initial experience in estimating hemiliver graft weights for split liver transplantation with maximal portal vein diameters derived from bedside abdominal ultrasonography; the discrepancy between the calculated hemiliver graft weights and the AGWs for 4 liver donors was less than 4%.[37] However, further studies are required to correlate ultrasound-measured portal vein diameters with AGWs.

In conclusion, the maximal PVDR method is an easy and simple estimation method that can accurately predict right lobe GV/weight values in adult LDLT.

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