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ORIGINAL ARTICLE

Variability of Standard Liver Volume Estimation Versus Software-Assisted Total Liver Volume Measurement

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The estimation of the standard liver volume (SLV) is an important component of the evaluation of potential living liver donors and the surgical planning for resection for tumors. At least 16 different formulas for estimating SLV have been published in the worldwide literature. More recently, several proprietary software-assisted image postprocessing (SAIP) programs have been developed to provide accurate volume measurements based on the actual anatomy of a specific patient. Using SAIP, we measured SLV in 375 healthy potential liver donors and compared the results to SLV values that were estimated with the previously published formulas and each donor's demographic and anthropomorphic data. The percentage errors of the 16 SLV formulas versus SAIP varied by more than 59% (from −21.6% to +37.7%). One formula was not statistically different from SAIP with respect to the percentage error (−1.2%), and another formula was not statistically different with respect to the absolute liver volume (18 mL). More than 75% of the estimated SLV values produced by these 2 formulas had percentage errors within ±15%, and the formulas provided good predictions within acceptable agreement (±15%) on scatter plots. Because of the wide variability, care must be taken when a formula is being chosen for estimating SLV, but the 2 aforementioned formulas provided the most accurate results with our patient demographics. ***Liver Transpl 18:1083-1092, 2012.*** © **2012 AASLD.**

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An important component of the donor evaluation for living donor liver transplantation (LDLT) is the determination of the hepatic venous and arterial anatomy, the standard liver volume (SLV), and the anticipated graft size. An accurate SLV estimate can be used to predict the liver graft volume; this is critical for preventing small-for-size syndrome in the recipient and ensuring an adequate remnant liver volume in the donor. The estimation of SLV can also be useful for surgical planning for resection for tumors and may be an important component in determining hepatic drug clearance in pharmacokinetic studies.[1,2] Because many surgical, physiological, and scientific calculations depend on SLV estimates, it is important to determine which formula provides the most accurate results.

Imaging hardware and protocols have improved consistently over the years, and image postprocessing software has become so refined that detailed examinations of the liver with either multiphase computed tomography (CT) or dynamic magnetic resonance imaging can be routinely performed at most transplant centers. More recently, several proprietary software programs using multiphasic helical CT data sets have been developed that can determine total liver organ and segmental volumes on the basis of the actual organ (as imaged), delineate surgical planes, define anatomical landmarks of the hepatic vasculature and biliary structures, and calculate anticipated postresection graft and remnant liver volumes.[3] Software-assisted image postprocessing (SAIP) provides

Abbreviations: BMI, body mass index; BSA, body surface area, BW, body weight; CT, computed tomography; LDLT, living donor liver transplantation; N/A, not available; SAIP, software-assisted image postprocessing; SD, standard deviation; SLV, standard liver volume.

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accurate data, but the associated postprocedural image processing is costly and time-consuming and to date has not been successfully automated. Instead, a highly trained operator needs to spend a significant amount of time postprocessing each case to obtain the desired results. The expense of high-end workstations and trained personnel may represent impediments to the use of SAIP in many clinical practice settings, especially in emerging or developing countries.

Historically, simple empirical formulas have been developed to estimate SLV with basic parameters such as the body weight (BW), body height, body surface area (BSA), age, and sex. These formulas may be useful as screening tools for estimating SLV in potential living liver donors or the residual volume anticipated after resection for tumors. In our review, we found that currently there are 16 published formulas for estimating SLV in the worldwide literature[4-18] (see Table 1). More recently, several authors have combined portal vein diameters and SLV estimates to calculate the hemiliver volume for split liver transplantation or LDLT.[21,22] In our clinical experience, SAIP volumetric studies using CT scans (ie, software-assisted CT scans) have been very accurate in predicting graft sizes with predetermined resection planes in comparison with actual graft volumes in living liver donors.[23] We found that software-assisted CT led to accurate right lobe graft calculations with a nonsignificant difference (17.5 mL) and a low percentage error (2.8%) in comparison with actual graft weights. Therefore, we consider SAIP liver volumetry to be the gold-standard technology for calculating the total organ liver volume, and it can also be used for calculating the anticipated graft size in LDLT. However, we and others have identified a problem with SAIP measurement: overestimation of the liver volume can occur because the blood volume within the liver is also included in the result. In a previous report from our center, Pomfret et al.[24] demonstrated that the actual right lobe liver graft weight was approximately 91% of the SAIP-estimated right lobe liver volume. This 9% volume reduction was attributed to intrahepatic blood that was flushed out of the liver by the preservation solution during back-table preparation. More recently, Satou et al.[25] reported similar findings. Back-table procedures significantly decreased the weight of the liver graft ($P < 0.02$). The graft weight after flushing with a preservation solution and the graft weight after backbench venous reconstruction were 95% and 90% of the weight obtained before flushing, respectively. Finally, Kim et al.[26] noted an average blood volume of 9.5% in right lobe grafts procured for LDLT. Therefore, we routinely correct SLV values obtained by SAIP by 9% before further analysis to account for these changes related to the blood volume.

The purpose of this study was to compare corrected SAIP-based total liver volume calculations to SLV values estimated with 16 published SLV formulas in a large group of healthy potential liver donors. The variability of the calculated results and the percentage errors of the formulas versus SAIP are presented. Because of the importance of accurate SLV determinations for a variety of applications, our goal was to identify which SLV formulas provided the most accurate estimates in comparison with SAIP.

PATIENTS AND METHODS

This study was approved by the institutional review board of Lahey Clinic before its initiation. Between December 1998 and January 2011, 382 healthy adults were considered as potential donors for LDLT and underwent the donor evaluation process. If no contraindication was found during the medical and psychological screening, contrast-enhanced, multiphasic, multidetector CT and subsequently SAIP were performed to determine the total and hemiliver volumes and the vascular and biliary anatomy. Donor demographics (age and sex) and anthropometric data [BW, body height, and body mass index (BMI)] were recorded prospectively during the evaluation process. Seven donors with incomplete data were excluded from the study, and this left 375 potential donors with complete data to be enrolled into the study. Two hundred twenty-five of these 375 donor candidates actually underwent successful right lobe (n = 222) or left lobe donation (n = 3). Some donors were rejected because of both donor and recipient factors.[27]

SLV Calculation

Sixteen SLV formulas identified in the literature were used to calculate SLV with each donor's demographic and anthropometric data (Table 1). Most of these formulas use simple subject-specific parameters such as age, sex, weight, and height. BSA was calculated with either the Du Bois–Du Bois formula[19] or Mosteller's formula[20] (Table 1). All results were recorded in a comprehensive database.

SAIP Liver Volume Measurement

Potential donors that were included in this study underwent dynamic, contrast-enhanced, multidetector CT scans of the abdomen and pelvis as part of their evaluation. The scanners included a General Electric LightSpeed Ultra CT scanner (General Electric HealthCare), a General Electric LightSpeed volume CT scanner (General Electric HealthCare), and a Siemens Definition dual-source CT scanner (Siemens Healthcare). The resulting images were stored in the institutional picture archiving and communication system at the time of acquisition and were also sent to MeVis Distant Services (Bremen, Germany) by a secure and encrypted Web transfer for anatomic and volumetric image postprocessing with LiverAnalyzer, the company's proprietary software assistant. This software has been validated, is Food and Drug Administration–approved, and has been successfully used in the planning of more than 4500 clinical LDLT cases worldwide. The validation of the software assistant in

TABLE 1. Various Formulas Used for Estimating SLV

Study	Formula	Population: Country	Population: Patients (n)	Population: Mean Age (Years)*	Adjusted R^2 Value for the Regression Analysis	Study Method
DeLand and North[4] (1968)†	1020(BSA) − 220	United States	625	N/A (N/A)	N/A	Postmortem examination in adults
Urata et al.[5] (1995)†	706.2(BSA) + 2.4	Japan	96	11.1 (<1-27)	0.96	CT volumetry
Noda et al.[6] (1997)	50.12 × $(BW)^{0.78}$	Japan	54	N/A (<1-22)	N/A	CT scan with image analyzer software in children and young adults
Lin et al.[7] (1998)	13(Height) + 12(BW) − 1530	Taiwan	33	50.0 (25-67)	0.83	CT volumetry in adults
Heinemann et al.[8] (1999)†	1072.8(BSA) − 345.7	Germany	1332	50.6 (N/A)	0.30	Postmortem examination in adults
Vauthey et al.[9] (2002)‡	1. 18.51(BW) + 191.8 2. 1267.28(BSA) − 794.41	United States, Switzerland, and Belgium	292	54 (14-90)	0.49	CT volumetry for transplantation or resection in adult patients
Yoshizumi et al.[10] (2003)‡	772(BSA)	United States	1413	41.9 (<1-87)	0.46	Cadaveric liver graft weight from adult and pediatric donors
Yu et al.[11] (2004)	21.585 × $(BW)^{0.732}$ × $(Height)^{0.225}$	Korea	652	42.4 (<1-90)	0.59	Postmortem examination in children and adults
Choukèr et al.[12] (2004)	16.434(BW) + 11.85(Age) − 166(Sex factor) + 452§	Germany	728	46.5 (16-70)	0.38	Postmortem examination in adults
Johnson et al.[13] (2005)†	1000$(0.72\sqrt{BSA} + 0.171)^3$	Many countries‖	4741	N/A (16-91)	N/A	Meta-analysis
Hashimoto et al.[14] (2006)†	961.3(BSA) − 404.8	Japan	301	N/A (17-66)	0.58	CT volumetry in adult LDLT donors
Chan et al.[15] (2006)	12.29(BW) + 50.74(Sex factor) + 218.32¶	China	159	35.8 (18-57)	0.48	SLV calculated from the right lobe liver graft volume divided by the right lobe proportion from CT
Yuan et al.[16] (2008)†	949.7(BSA) − 48.3(Age factor) − 247.4#	China	112	48.7 (19-73)	0.53	CT volumetry in adult
Fu-Gui et al.[17] (2009)	11.508(BW) + 334.024	China	115	36.0 (19-57)	0.44	SLV calculated from the right lobe liver graft volume divided by the right lobe proportion from CT
Poovathumkadavil et al.[18] (2010)	12.26(BW) + 555.65	Saudi Arabia	351	49.2 (N/A)	0.36	CT volumetry in adult

*Ranges are shown within parentheses.

†BSA is determined with the Du Bois–Du Bois formula[19]:

$$BSA = 0.007184 \times Height^{0.725} \times BW^{0.425}$$

where the height is measured in centimeters and BW is measured in kilograms.

‡BSA is determined with Mosteller's formula[20]:

$$BSA = \sqrt{(Height \times BW/3600)}$$

where the height is measured in centimeters and BW is measured in kilograms.

§Sex factor: female = 1 and male = 0.

‖Belgium, Germany, Japan, Switzerland, the United Kingdom, and the United States.

¶Sex factor: male = 1 and female = 0.

#Age factor: <40 years = 1, 41-60 years = 2, and >60 years = 3.

calculating the volume of hepatic vascular territories has been previously described by Selle et al.[28] The clinical use of this software for surgical planning for LDLT has also been described previously.[29-31] Each liver was segmented by the interpolation of multiple individual organ contours that were drawn, and the total liver volume was calculated by the addition of the volumes of all enclosed imaging voxels; thus, the corresponding organ volume was calculated in cubic centimeters. Images of the liver were further processed to provide the delineated vascular and biliary anatomy and the total and segmental liver volumes. After an SLV value was obtained by SAIP calculation, the result was reduced by 9% for the blood volume before it was compared to the results of the other estimation methods.[24-26]

TABLE 2. Characteristics of All 375 Potential Donors

Characteristic	Value
Age (years)	38.2 ± 10.6 (18-59)
BW (kg)	79.0 ± 15.9 (45.8-123.0)
Body height (cm)	171.2 ± 10.1 (147.3-195.6)
BMI (kg/m^2)	26.8 ± 3.8 (17.3-38.8)
BSA by the Du Bois–Du Bois formula[19] (m^2)	1.91 ± 0.23 (1.40-2.47)
BSA by Mosteller's formula[20] (m^2)	1.93 ± 0.24 (1.41-2.52)

NOTE: The data are presented as means and SDs (with minima and maxima in parentheses).

Statistical Analysis

All analytical tests were performed with SPSS 14 (IBM SPSS, Chicago, IL). Descriptive data were reported as means and standard deviations (SDs). The volume difference between the results of each SLV formula and SAIP was demonstrated with the number and the percentage error [(estimated SLV − SAIP value)/SAIP value × 100]. A repeated measures analysis of variance was used to analyze the significance of the volume difference and the percentage error between the calculated SAIP value and the estimated SLV value. We used ±10% and ±15% as acceptable ranges for differences between SLV estimates and SAIP calculations, and the proportions of estimates within these acceptable ranges (shown as percentages) were determined for each SLV formula.[18,32] These percentages were compared via McNemar's test with the highest percentage used as the reference for comparison. The statistical significance was set at $P < 0.05$ for all tests.

Scatter plots with fitted lines were used to illustrate the correlation between the calculations of each SLV formula and SAIP-calculated liver volumes. Reference lines showed the perfect correlation for each SLV formula and SAIP-derived volumes. Only formulas with clinically insignificant percentage errors (<5%) were chosen for further analysis. To verify the agreement of

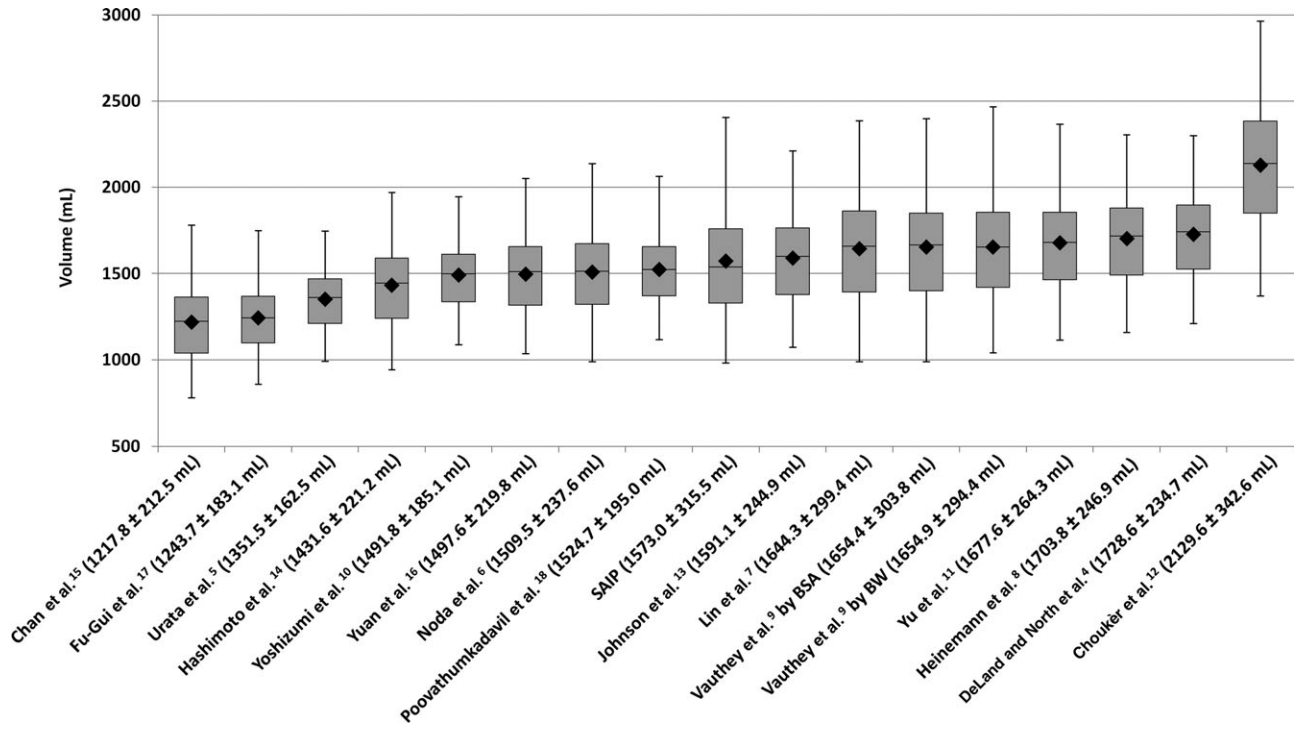

Figure 1. Box plots of the SLV values estimated with the 16 formulas and SAIP. In each box, the horizontal line in the middle is the median; the black diamond is the mean; the lower and upper borders are the 25th and 75th percentiles, respectively; and the lower and upper whiskers are the minimal value to the 25th percentile and the 75th percentile to the maximal value, respectively. The estimated results varied by 59% and depended on the formulas.

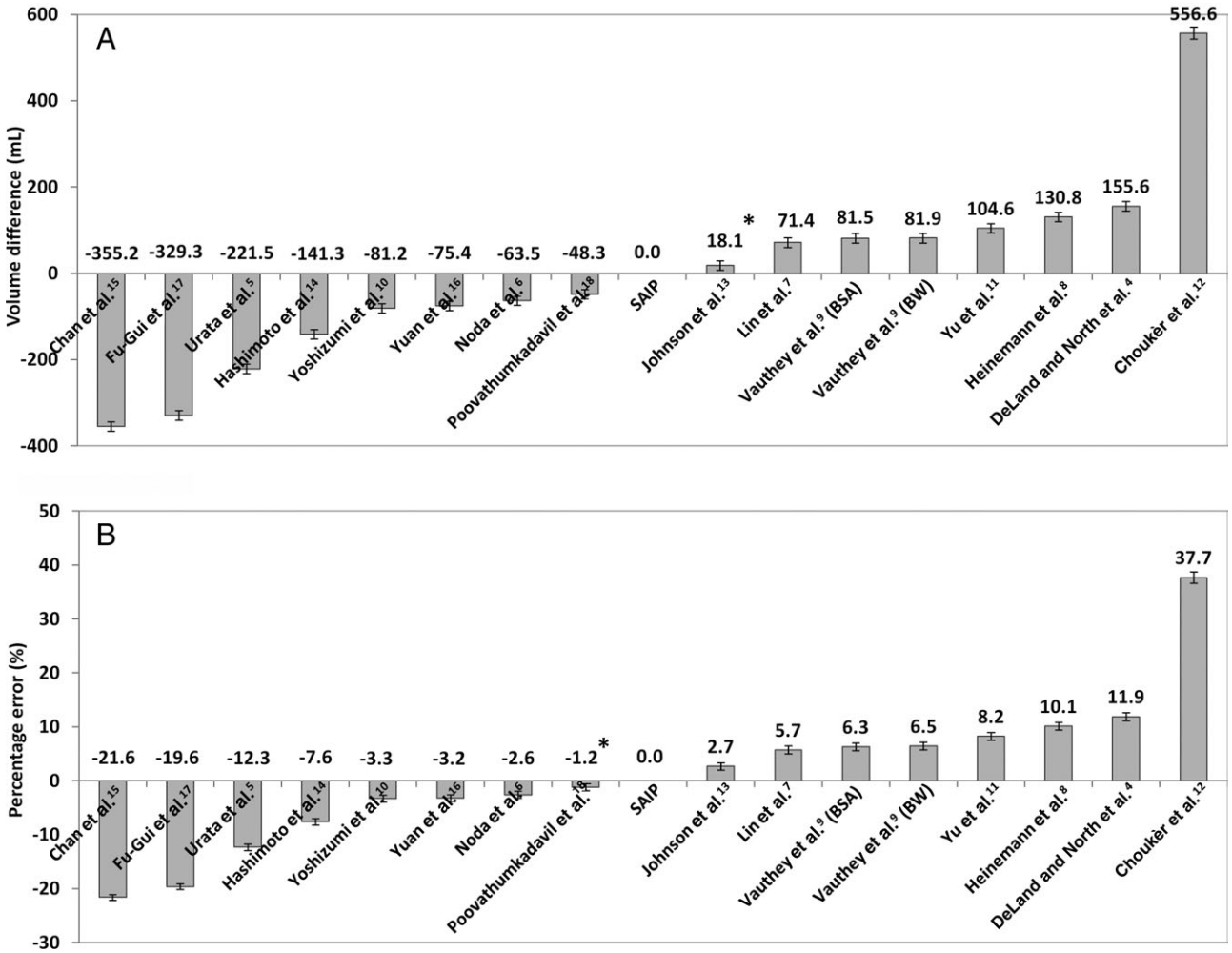

Figure 2. (A) Absolute volume differences between the SLV values estimated with each formula and the SAIP-derived values. (B) Percentage errors of the SLV values estimated with each formula versus the SAIP-measured values. Except for Johnson et al.'s formula[13] (the absolute volume difference) and Poovathumkadavil et al.'s formula[18] (the percentage error), all the formulas produced values that were statistically significantly different from the SAIP-derived values. The error bars show the standard errors of the mean. An asterisk indicates nonsignificance (ie, $P > 0.05$).

each formula with the SAIP-based volume calculations, the volume differences between the calculated SLV values and the SAIP-derived volumes were plotted against the SAIP estimates with the modified Bland-Altman method.[33]

RESULTS

The demographic and anthropometric data, including age, sex, BW, height, BMI, and BSA, were gathered for all 375 donors and are shown in Table 2. The majority of the donors were male (55.2%) and middle-aged (56% were within the range of 30-50 years). Forty percent of the donors were slightly overweight (BMI = 25-29.9 kg/m^2), and 36.3% had a normal height for their weight (BMI = 18.5-24.9 kg/m^2). The SLVs of all 375 donors with complete data were calculated with all 16 formulas listed in Table 1, and they are presented as means and SDs via box plots in Fig. 1. The results show the wide range of estimated volume differences (approximately 59%): the smallest volumes were calculated with Chan et al.'s formula[15] (1217.8 ± 212.5 mL), and the largest ones were calculated with Choukèr et al.'s formula[12] (2129.6 ± 342.6 mL).

The results of pairwise comparisons of volume results from each SLV formula and SAIP-derived volumes are shown in Fig. 2. All formulas except Johnson et al.'s formula[13] resulted in estimated SLV values that were statistically significantly different from SAIP-derived volumes [$F_{3.07,1149.50} = 2569.18$ ($P < 0.05$) according to a repeated measures analysis of variance]. The percentage errors of the formula-derived results versus the SAIP-derived volumes varied by more than 59% and ranged from an underestimation of 21.6% with Chan et al.'s formula[15] to an overestimation of 37.7% with Choukèr et al.'s formula,[12] as shown in Fig. 2. The result from a comparison of the percentage errors with an analysis of variance was $F_{2.52,942.27} = 2725.97$ ($P < 0.05$), with only Poovathumkadavil et al.'s formula[18] providing a

TABLE 3. Proportions of Estimated SLV Results With Percentage Errors Within Acceptable Agreement (±10% and ±15%[18,32]) in Comparison With SAIP Calculations

	Proportion Within Acceptable Agreement (%)			
SLV Formula	±15%	*P* Value	±10%	*P* Value
Yuan et al.[16] (2008)	77.1	—	57.6	—
Poovathumkadavil et al.[18] (2010)	75.7	0.53*	57.1	0.90*
Noda et al.[6] (1997)	75.7	0.54*	54.9	0.22*
Yoshizumi et al.[10] (2003)	75.5	0.26*	56.0	0.44*
Johnson et al.[13] (2005)	75.0	0.39*	56.0	0.61*
Hashimoto et al.[14] (2006)	70.4	<0.01	51.7	<0.01
Vauthey et al.[9] (2002)†	69.9	0.02	49.6	0.03
Lin et al.[7] (1998)	68.8	<0.01	50.9	0.04
Vauthey et al.[9] (2002)‡	68.5	<0.01	49.6	0.02
Yu et al.[11] (2004)	66.9	<0.01	46.1	<0.01
Heinemann et al.[8] (1999)	61.9	<0.01	41.3	<0.01
Urata et al.[5] (1995)	60.5	<0.01	38.9	<0.01
DeLand and North[4] (1968)	56.8	<0.01	36.8	<0.01
Fu-Gui et al.[17] (2009)	31.2	<0.01	17.1	<0.01
Chan et al.[15] (2006)	23.7	<0.01	12.5	<0.01
Choukèr et al.[12] (2004)	12.0	<0.01	5.9	<0.01

*Nonsignificant (ie, $P > 0.05$).
†BW formula.
‡BSA formula.

nonsignificant percentage error in comparison with SAIP. Although the formulas of Noda et al.[6] and Johnson et al.[13] produced results that were statistically different from SAIP-derived values, the percentage errors were relatively small (−2.6% and +2.7%, respectively) and probably clinically insignificant.

The proportions of calculated results with percentage errors within acceptable agreement (±10% and ±15%) are shown in Table 3. The highest proportions for both levels of agreement came from Yuan et al.'s formula.[16] There were 4 other formulas that led to nonsignificant differences in proportions similar to those achieved with Yuan et al.'s formula: Poovathumkadavil et al.'s formula,[18] Noda et al.'s formula,[6] Yoshizumi et al.'s formula,[10] and Johnson et al.'s formula.[13]

Figure 3 correlates SAIP and 5 selected formulas (Poovathumkadavil et al.,[18] Noda et al.,[6] Johnson et al.,[13] Yuan et al.,[16] and Yoshizumi et al.[10]); each formula had a percentage error < 5%, and the proportion of SLV results within acceptable agreement (±15%) was ≥75%. All the formulas had significant correlations with similar R^2 values (range = 0.56-0.57). Johnson et al.'s formula showed the widest range of acceptable agreement (from approximately 1200 mL to approximately 2500 mL). The same could be seen in modified Bland-Altman plots (Fig. 4), which also demonstrated that the estimates of SLV became less precise as the predicted SLV value increased.

DISCUSSION

The accurate determination of the total liver volume is an important consideration for a variety of surgical, physiological, and pharmacological applications. In our experience, SAIP has been proven to be the most accurate method for calculating liver segmental and total volumes and vascular and biliary anatomy. Previously, our group compared right lobe graft volumes estimated by SAIP with actual graft weights measured during LDLT and reported a nonsignificant volume difference of approximately 17.5 mL and a low percentage error of approximately 2.8%.[23] The disadvantage of this method is that the technology is resource-intense and incurs costs because of the requisite time and postprocessing labor involved; this may be an obstacle in some clinical settings. However, the availability of commercial web-based remote postprocessing sites potentially allows widespread access to this technology. Another shortcoming of SAIP is that it does not correct for the blood volume during the calculation. In this study, we corrected SAIP-calculated volumes by subtracting 9% (a figure based on our previous findings) to account for the volume of intrahepatic blood.[24] This is consistent with the findings of Kim et al.,[26] who measured blood-filled and blood-free liver volumes with automatically outlined CT volumetry and estimated the percentage of the blood volume inside the liver to be approximately 9.5% (range = 6.5%-19.8%), and with the more recent and similar findings of Satou et al.[25]

Although complicated liver surgery often requires very accurate investigations to determine the liver volume and delineate intrahepatic vital structures, a simple method for estimating SLV could be helpful in some clinical settings. For example, an accurate SLV estimation can be useful as a screening tool for assessing potential living liver donors before any other

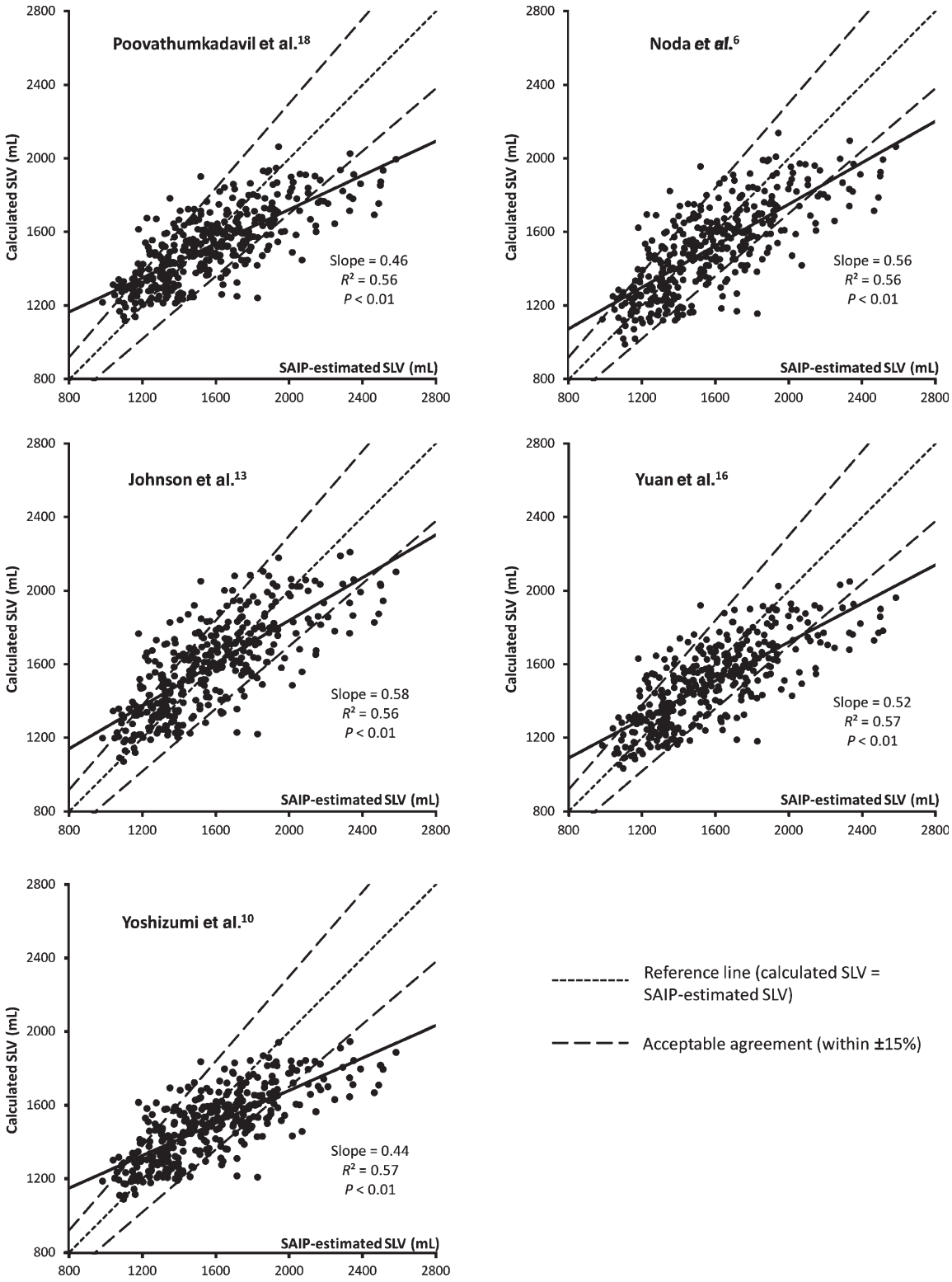

Figure 3. Scatter plots and fitted lines showing the correlation between SAIP-derived values and SLV values estimated with the 5 SLV formulas with percentage errors within ±5%. All these formulas show significant correlations with SAIP. The fitted line for Johnson et al.'s formula[13] runs closest to the reference line with the widest range of prediction within acceptable agreement (±15%).

expensive or invasive investigations are performed. This is especially important for programs with limited resources or in parts of the world with limited technology. In addition, it may be useful for pharmacokinetic studies of new drugs for which the real liver size measurement is not feasible but is desirable. Obviously, such measurements or estimates of SLV are related to the liver mass and not the liver function.

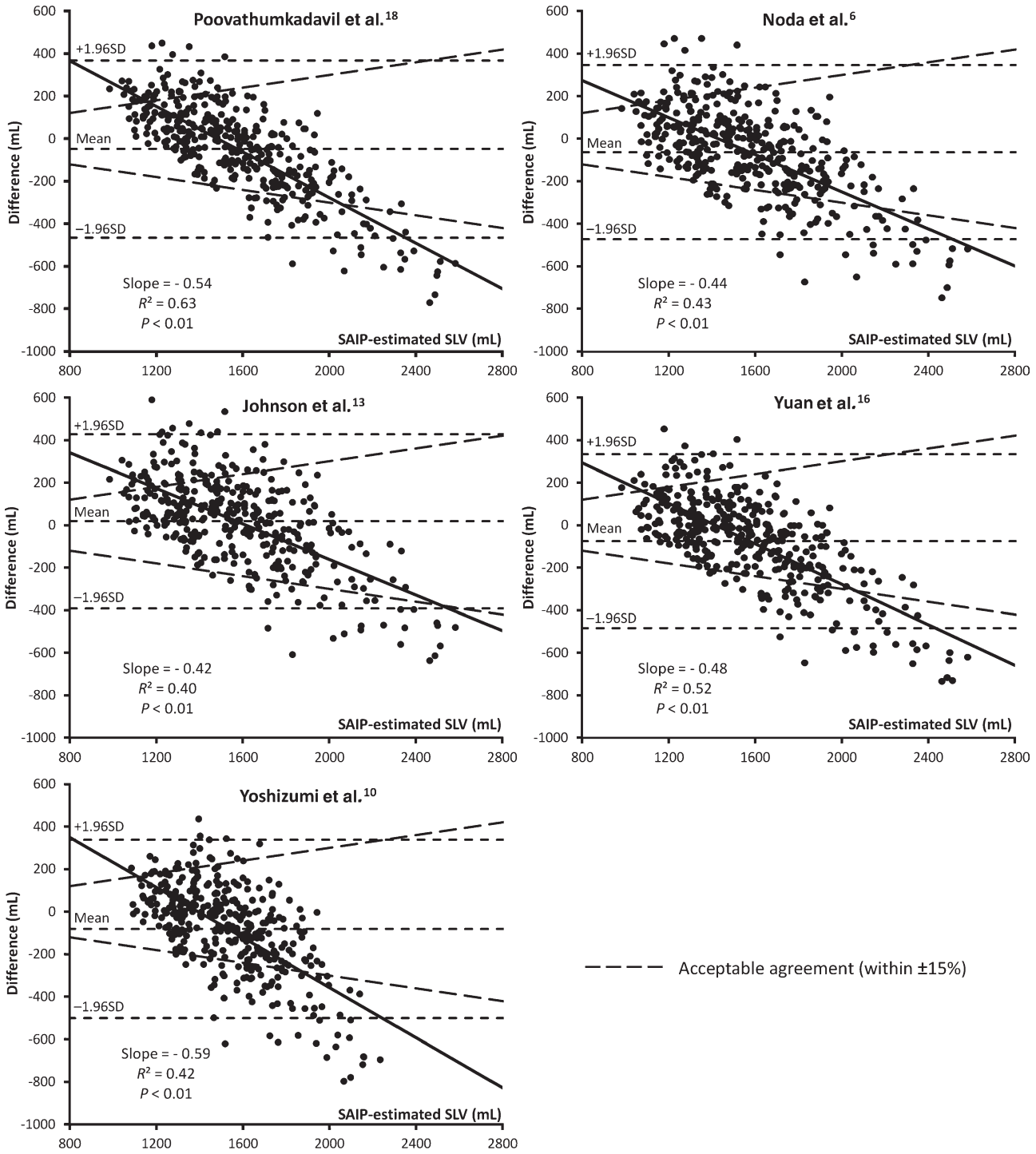

Figure 4. Modified Bland-Altman plots of the volume differences (calculated SLV value − SAIP-derived value) and the SAIP estimates. All the presented formulas tend to underestimate SLV more than SAIP when the liver volume is larger. Johnson et al.'s formula[13] seems to lead to the least underestimation and the widest range of prediction within acceptable agreement (±15%).

Because most SLV formulas have been generated from data from healthy liver populations, caution is advised when chronically diseased patients are being evaluated because the results may underestimate or overestimate the functional capacity according to the clinical situation. In our transplant program, SLV and hemiliver volume estimations are still considered investigational, but if their accuracy could be improved with refinements of the formulas used, we would use these simple screening tools during the initial assessment of potential donors before we performed more invasive and expensive investigations.

The estimates of SLV based on our donor demographics varied by 59% and depended on the method used. This observation would be expected to raise

concerns for clinicians who are considering a formula for liver volume determination. In a recent report, Yoshizumi et al.[32] calculated SLV in 70 healthy adults with CT volumetry and reported nonsignificant differences with SLV values estimated with the formulas of Noda et al.,[6] Vauthey et al.,[9] and Yoshizumi et al.[10] More recently, Poovathumkadavil et al.[18] showed that Vauthey et al.'s formula and their own SLV formula provided good results. They also demonstrated that the SLV percentage error ranged from −17% to +32%, with the smallest estimation coming from Fu-Gui et al.'s formula[17] and the largest coming from Choukèr et al.'s formula.[12] Both studies demonstrated that Urata et al.'s formula[5] underestimated SLV, whereas the DeLand-North's formula[4] and Heinemann et al.'s formula[8] overestimated SLV; this is consistent with our findings. Interestingly, the 4 formulas that overestimated SLV (DeLand and North,[4] Heinemann et al.,[8] Yu et al.,[11] and Choukèr et al.[12]) were established with autopsy examinations. Poovathumkadavil et al. presumed that other structures attached to the liver (the gallbladder, ligaments, and vessels) and perimortem cardiovascular events (shock and heart failure) could have resulted in fluid shifts and heavier liver weights. On the other hand, the formulas of Chan et al.[15] and Fu-Gui et al.[17] provided the smallest estimates of SLV, and both formulas were established with the back-table right lobe graft volume divided by the right lobe proportion based on CT volumetry. Yoshizumi et al.'s formula[10] was established with whole liver weights measured on the back table during adult liver transplantation and provided SLV estimates comparable to those from other formulas established with CT volumetry.[5-7,9,14,16,18] It is important to note that some formulas were generated from autopsy examinations or intraoperative measurements based on the liver weight (not the volume). However, the density of the liver is sufficiently similar to the density of water and has been reported to be 1 g/mL.[17,25,34]

In our study, Johnson et al.'s formula[13] provided very accurate results in terms of the absolute volume with respect to SAIP. Johnson et al. performed a meta-analysis of previous studies predicting liver size in children and adults to develop their formula. For adults (>18 years old), they suggested that their equation and Vauthey et al.'s BSA model[9] were favorable because of their good precision and low bias. On the other hand, Poovathumkadavil et al.'s formula[18] showed the least difference in terms of the percentage error versus SAIP. No single formula was statistically comparable with SAIP for both parameters (ie, the absolute volume and the percentage error). Yuan et al.'s formula[16] had the highest proportion of percentage errors within acceptable agreement (±10% and ±15%). Four other formulas, all of which had average percentage errors < 5%, also had comparably high proportions of errors (≥75%) within acceptable agreement (±10% and ±15%). These formulas included the 2 previously mentioned ones as well as the formulas of Noda et al.[6] and Yoshizumi et al.[10]

The formulas of Chan et al.[15] and Choukèr et al.[12] underestimated and overestimated SLV, respectively, in terms of volume differences and percentage errors. Fu-Gui et al.'s formula[17] also underestimated SLV with a mean percentage error of approximately −20%. For these 3 formulas, <50% of the calculated SLV values and percentage errors were within the acceptable agreement range of ±15%. Because of these inferior results, we would discourage the use of these formulas.

Scatter plots and modified Bland-Altman plots of the 5 most accurate formulas are shown in Figs. 3 and 4, respectively, and they demonstrate that as the anticipated SLV value increased, the accuracy of these formulas decreased, especially with larger liver volumes. This finding was also reported by Yoshizumi et al.[32]: the formulas of Noda et al.[6] and Yoshizumi et al.[10] underestimated SLV when the liver volume was >1600 mL. In this study, the scatter plots and the modified Bland-Altman plots suggest that the formulas provide good predictions of SLV with acceptable agreement (±15%) between 1200 and 2000 mL. Exceptions include the formulas of Noda et al.[6] and Johnson et al.,[13] whose range of acceptable agreement is a little wider. Johnson et al.'s formula seems to be the best in terms of the widest accurate prediction range (from approximately 1100 to 2500 mL). The fact that SLV is underestimated for larger livers might not be surprising because the formulas assume a linear relationship between BW and liver volume. However, as BW increases, the proportion of less metabolically active tissue such as adipose tissue also increases, and this is not likely to be associated with a proportional increase in the liver volume. Despite these observations, the estimations of SLV seemed to be reliable for a wide range of individuals.

Interestingly, only 2 of the 16 formulas (Chan et al.[15] and Choukèr et al.[12]) count sex as an important factor affecting SLV calculations. However, the results with these formulas were significantly different from the SAIP results. None of the 5 most accurate formulas include sex. With the exception of Yuan et al.'s formula,[16] which also uses age as a significant factor, these formulas use only 1 datum (eg, BW or BSA). Surprisingly, 3 of the 5 most accurate formulas were derived from studies of non-Caucasian populations. These findings suggest that the liver volume is dictated more by the body size (eg, BW or BSA) than the race of the individual. Also, supportive evidence has indicated no differences in the BSA-normalized liver volumes of Japanese and Caucasian adults, as reported by Johnson et al.[13]

Because of the wide variability of the obtained results, care must be taken when an equation for estimating SLV is being chosen. For precise measurements of SLV, SAIP is preferred because the liver volume is calculated on the basis of CT or magnetic resonance imaging data sets rather than a formula derived from patient parameters. However, SLV-calculating formulas might still be useful in some previously mentioned clinical settings. Although no single formula provided a perfect fit with all our statistical analyses, we found that Johnson et al.'s formula[13]

was the most accurate in terms of the absolute volume over a wide range of liver volumes and had a relatively low percentage error. Poovathumkadavil et al.'s formula[18] provided the lowest percentage error versus SAIP and would also be a good second choice in our opinion. Additional studies are needed to verify these results and to refine SLV equations for more accurate SLV estimation.

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