European Journal of Radiology 81 (2012) 2042–2048

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Accurate perioperative flow measurement of the portal vein and hepatic and renal artery: A role for preoperative MRI?

Mechteld A.R. Vermeulen[a], Gerdien C. Ligthart-Melis[b], René Buijsman[a], Michiel P.C. Siroen[a], Marcel C.G. van de Poll[c], Petra G. Boelens[c], Cornelis H.C. Dejong[c], Cors van Schaik[d], Mark B.M. Hofman[e], Paul A.M. van Leeuwen[a,*]

[a] Department of Surgery, VU University Medical Center, P.O. Box 7057, 1007 MB Amsterdam, The Netherlands[1]
[b] Department of Internal Medicine, Dietetics and Nutritional Sciences, VU University Medical Center, P.O. Box 7057, 1007 MB Amsterdam, The Netherlands[1]
[c] Department of Surgery, Maastricht University Medical Center, P.O. Box 5800, 6202 AZ Maastricht, The Netherlands[2]
[d] Department of Radiology, VU University Medical Center, P.O. Box 7057, 1007 MB Amsterdam, The Netherlands[1]
[e] Department of Physics and Medical Technology, VU University Medical Center, P.O. Box 7057, 1007 MB Amsterdam, The Netherlands[1]

ARTICLE INFO

Article history:
Received 23 February 2011
Received in revised form 31 May 2011
Accepted 3 June 2011

Keywords:
Portal flow
Renal flow
Ultrasound
Flux
MRI
Liver transplantation

ABSTRACT

Background: Quantification of abdominal blood flow is essential for a variety of gastrointestinal and hepatic topics such as liver transplantation or metabolic flux measurement, but those need to be performed during surgery. It is not clear whether Duplex Doppler Ultrasound during surgery or MRI before surgery is the tool to choose.
Objective: To examine whether preoperative evaluation of abdominal blood flow using MRI could prove to be a useful and reliable alternative for the perioperative sonographic approach.
Methods: In this study portal and renal venous flow and hepatic arterial flow were sequentially quantified by preoperative MRI, preoperative and perioperative Duplex Doppler Ultrasound (DDUS). 55 Patients scheduled for major abdominal surgery were studied and methods and settings were compared. Additionally, average patient population values were compared.
Results: Mean (±SD) plasmaflow measured by perioperative DDUS, preoperative DDUS and MRI, respectively was 433 ± 200/423 ± 162/507 ± 96 ml/min (portal vein); 96 ± 70/74 ± 41/108 ± 91 ml/min (hepatic artery); 248 ± 139/201 ± 118/219 ± 69 ml/min (renal vein). No differences between the different settings of DDUS measurement were detected. Equality of mean was observed for all measurements. Bland Altman Plots showed widespread margins. Hepatic arterial flow measurements correlated with each other, but portal and renal venous flow correlations were absent.
Conclusions: Surgery and method (DDUS vs. MRI) do not affect mean flow values. Individual comparison is restricted due to wide range in measurements.

Since MRI proves to be more reliable with respect to inter-observer variability, we recommend using mean MRI results in experimental setups.

1. Introduction

Blood flow measurement using Duplex Doppler Ultrasound (DDUS) is a widely used technique for measuring blood flow in a variety of vessels. Blood flow quantification is an essential instrument for detecting or monitoring vascular pathology and evaluating therapeutic interventions [1–4]. Before surgery, for example in case of liver transplantation, before TIPS and before kidney donor transplantation. During surgery flow measurement is specifically used for metabolic purposes, i.e. organ flux measurement. This is a measure of net exchange across organs (net flux = [vein] − [artery] × plasma flow) [5,6].

Techniques to visualize and assess blood flow both quantitatively and qualitatively have developed over the past decades. Besides the sonographic approach magnetic resonance imaging

---

Abbreviations: DDUS, Duplex Doppler ultrasound; GIST, gastro intestinal stroma tumor; HA, hepatic artery; MRI, magnetic resonance imaging; PV, portal vein; ROI, region of interest; RV, renal vein.

* Corresponding author. Tel.: +31 20 444 4444; fax: +31 20 444 3620.
E-mail addresses: mar.vermeulen@vumc.nl (M.A.R. Vermeulen), g.ligthart-melis@vumc.nl (G.C. Ligthart-Melis), renebuysman@gmail.com (R. Buijsman), m.siroen6@upcmail.nl (M.P.C. Siroen), mcg.vandepoll@ah.unimaas.nl (M.C.G. van de Poll), p.boelens@mumc.nl (P.G. Boelens), chc.dejong@mumc.nl (C.H.C. Dejong), c.vanschaik@vumc.nl (C. van Schaik), mbm.hofman@vumc.nl (M.B.M. Hofman), pam.vleeuwen@vumc.nl (P.A.M. van Leeuwen).
[1] Tel.: +31 20 444 4444; fax: +31 20 444 4645.
[2] Tel.: +31 43 387 6543.

doi:10.1016/j.ejrad.2011.06.023

(MRI) has proved to be a complementary way for quantifying blood flow non-invasively [2,7–10].

A general disadvantage of the sonographic approach of blood flow measurement is inter- and intra-observer variability [11]. Since MRI proves to be more reliable with respect to inter-observer variability, this could represent a more accurate alternative for blood flow measurement [12]. However, for organ flux measurement, unfortunately immobility of the MRI machine disqualifies its use for perioperative purposes.

For a reliable measurement of organ flux, adequate sampling of the substance of choice and reliable blood flow measurements are of paramount importance for quantification of that particular substance across organs. However, flux calculation across organs that are drained by vessels that are relatively inaccessible (abdominal veins and arteries) is challenging. First, blood sampling cannot easily be performed in vessels covered by vital organs. To overcome this problem, sampling is often performed during abdominal surgery. Secondly as a consequence, flow measurement should also be performed during surgery. For example, for splanchnic flow quantification, both the portal vein and the hepatic artery need to be examined. This is technically possible with DDUS, yet difficulties are involved: the perioperative approach of flow measurement can prolong the duration of surgery and measurements naturally have to be performed within a sterile setting.

Theoretically, MRI is superior to DDUS because of more pronounced accuracy and less inter-observer variability [12]. MRI, unfortunately, is currently not possible during surgery. Since the desired setting of flow measurement is during surgery, this technique is only suitable when it proves to be adequate in predicting perioperative blood flow.

The aim of this study is to examine by a two-step approach whether a preoperative evaluation of blood flow using MRI could prove to be a useful and accurate alternative for the perioperative sonographic approach used at present in metabolic flux studies. To reinsure that possible differences reflect the method used instead of being a direct result of the surgical setting, DDUS measurements were performed both perioperatively and preoperatively.

2. Materials and methods

2.1. Subjects

All patients admitted to the VU University Medical Center (VUmc) scheduled for major abdominal surgery from January 2003 until July 2005 were included when they met inclusion criteria. These patients were studied prospectively as a separate part of the studies of Ligthart-Melis et al. and Siroen et al. [5,6] Subjects were thoroughly informed, whereupon written informed consent for all parts of the studies was obtained. Briefly, inclusion criteria were major abdominal surgery, age between 18 and 75. Patient characteristics are displayed in Table 1.

To resemble the preoperative situation, care was taken to measure the preoperative blood flow at a similar time of the day as the patient was scheduled for surgery. Furthermore, patients were assessed in the postabsorptive state.

The study was approved by the institutional board and the medical ethical review committee of our hospital and accorded to the ethical standards of the Helsinki Declaration as revised in 1983.

The analyses were performed on a vessel basis. In order to be included in the analysis, two of three measurements (perioperative DDUS, preoperative DDUS and MRI) had to be obtained in a specific patient, otherwise data points were excluded. Noteworthy, comparison between setting (DDUS before vs. during surgery) and method (preoperative MRI vs. preoperative DDUS) necessitated the presence of preoperative DDUS measurements.

Data excluded in case of vascular anomalies were scored on the contrast-enhanced MRA sequence.

2.2. Flow measurement

2.2.1. DDUS

The principles of Doppler US are well described by Gill [13]. In this study, an Aloka Prosound SSD 5000 (Aloka Co., Ltd., Tokyo, Japan) was used for both the preoperative and perioperative DDUS measurements, using a 7.5 MHz probe. All measurements were performed by a senior radiologist or a Doppler US educated radiology assistant, both with more than 10 years of experience in Doppler examination of deep abdominal vessels. Doppler settings were optimized in each case according to common practice. The hepatic artery and portal and renal vein were assessed enabling calculation of splanchnic and renal metabolism. All vessels were first visualized in B-mode (black and white). Measurements were performed while the patient suspended his or her inspiration after which the Doppler spectrum was recorded. After correcting for the angle of insonation, the mean blood flow velocity was calculated online. Cross-sectional areas of the vessels were determined by drawing an area ellipse at the same location at which the velocity measurement was performed. For accurate velocity measurements, care was taken to keep the angle between the ultrasonic beam and blood flow direction below 60° [14]. The Doppler sample volume was positioned in the centre of the vessel and varied in width to detect the clearest Doppler frequency shift signal. Measurements were taken during at least three cardiac cycles. Blood flow was measured in the hepatic artery, portal vein and renal vein in the postabsorptive state in supine position. Flow measurements of the portal vein were performed before hilar bifurcation. Hepatic arterial flow was measured after the gastroduodenal artery had branched off, but before bifurcating into the left and right hepatic arteries. In cases with aberrant left or right hepatic arteries, all vessels were measured separately.

Preoperative measurement was performed after a rest of 15 min, as recommended by Brown et al. [14].

Perioperative flow measurements took place after incision of the abdominal wall and exposure of the organs involved in the surgical procedure, but before start of organ resection. To prevent anesthetic effects on blood flow, the procedure was standardized as much as possible by preferably using isoflurane or sevoflurane [5,6].

For both the preoperative and perioperative examination, the same probes were used and examinations were performed by the same operator.

2.2.2. MR flow quantification

The principles of phase-contrast MRI flow quantification have been described in detail by Debatin [15]. The measurement protocol was standardized as follows: a 1.5 T whole body MR system (Magnetom Sonata, Siemens, Erlangen, Germany) was applied with a phased array surface RF receiving coil. For localization coronal, transversal, sagital, and sometimes oblique scouts were obtained, with an SSFP-pulse sequence with a spatial resolution of 1.6 mm × 1.4 mm × 5.0 mm.

The position of flow measurement was determined on the localizer images. Hepatic arterial flow was measured after the gastroduodenal artery had branched off, if visible on the scouts. Both hepatic arterial flow and portal venous flow were measured before their hilar bifurcation.

The acquisition parameters for the MR phase contrast measurements were: an ECG triggered phase-contrast gradient echo pulse sequence, with a repetition time of 6 ms, an echo time of 3 ms, and a 25° excitation angle. For the portal vein and renal vein measurement the spatial resolution was 1.7 mm × 1.2 mm × 6.0 mm, and

Table 1
Characteristics of patients.

Characteristics	*N* (mean)	% (SD)	Diagnosis	Origin	*N*	%
Gender						
Male	41	75%	Liver metastases	Colorectal origin	41	75%
Female	14	26%		Gastric origin	1	2%
Age	61	±11		Ovarian origin	1	2%
Weight	82	±14		Melanoma	1	2%
BMI	27	±5		GIST	1	2%
Underweight	1	2%	Hepatocellular carcinoma		6	11%
Normal	12	22%	Pancreatic carcer		1	2%
Overweight	32	58%	Sarcoma		1	2%
Obesity	9	16%	Benign liver tumor		2	4%
Unknown	1	2%				

Characteristics of patients, data are shown as percentages or mean ± SD.

the velocity encoding value (V_{ENC}) was set at 30 cm/s. For hepatic artery measurements a slightly higher spatial resolution of 1.5 mm × 1.2 mm × 5.5 mm was applied with a V_{ENC} set at 80 cm/s. Patients were asked to hold their breath, after which flow measurements were taken during 19 heart cycles. After flow measurement completion, contrast was administered in order to detect any vascular anomalies, using contrast-enhanced MR [16].

Flow images were stored and analyzed using standard software (Argus, Siemens, Erlangen, Germany). Cross-sectional areas were drawn on the images to define the region of interest (ROI). Subsequently, a second ROI was drawn in a nearby area without any visible vessels; this ROI served as a control area. A cine-movie over the cardiac cycle was played to verify whether the ROI and reference ROI were drawn correctly. The volume flow was calculated by integration of the velocity over the cross-sectional area, and the cardiac cycle. Velocity values were compensated for stationary velocity offsets by use of the reference ROI. Analyses were performed by two observers. In case of discrepancy, analysis was performed on mutual agreement.

2.3. Blood sampling and calculation for plasma flow

After blood flow measurements were performed using both techniques, plasma flow was calculated by correcting for corresponding (preoperative vs. perioperative) hematocrit: plasma flow = blood flow × (1 − hematocrit).

2.4. Statistics

Results of the plasma flow measurements are expressed as mean and standard deviation in case of normal distribution (SD).

Pearson correlation test was used to detect correlations between the two settings (preoperative DDUS vs. perioperative DDUS) and to detect correlations between the different methods of measurement (preoperatively: DDUS vs. MRI).

Since a high degree of correlation does not entail good agreement between two methods, Bland–Altman plots (difference plots) were made. The limits of agreement during Bland–Altman analyses are specified as average difference ± 2SD (standard deviation of the difference).

Paired *T*-tests where performed to point out differences in the setting (preoperative DDUS vs. perioperative DDUS) and the methods (preoperatively: DDUS vs. MRI).

ANOVA (in case of equal variances) or Welch test (in case of unequal variances) was used to verify equality of means among setting and method.

Statistical analysis was performed with SPSS package software (SPSS 16.0 for Windows®). Statistical significance was defined as 2-tailed $P < 0.05$.

3. Results

3.1. Subjects and measurements

In total, 55 patients were subjected to flow assessment.

Incomplete or unreliable measurements were excluded from analysis. Incomplete Duplex DDUS were either due to absent Doppler shift signal mainly due to overweight (8 patients), or to procedural difficulties during the surgical course (5 patients). The reliability of the DDUS measurements per vessel was judged by evaluating the angle of insonation (<60°) (details per vessel are expressed below).

Incomplete MRI measurements were due to unavailability of the MRI-scanner (schedule difficulties or defects of the scanner) (22 patients), due to prosthetic devices interrupting magnetic signaling (1 patient), incorrect procedure of measurements (1 patient), claustrophobia (2 patients), or refusal of the patient (1 patient). MRI measurement reliability depended on breath hold adequacy. Retrospectively, reliability was again judged using the images. In case of strong image ghosting artefacts due to patient motion during the measurement, results were excluded from analyses.

3.1.1. Portal vein measurements

DDUS was performed during surgery in 50 patients, whereas in 5 patients measurements were not possible for abovementioned reasons. Retrospectively, 7 of 50 measurements were performed in one of the portal vein's branches and were therefore excluded from analyses.

In 47 patients flow in the portal vein was measured prior to surgery, using DDUS; in 8 patients measurements were not possible for abovementioned reasons. Retrospectively, 3 of the 47 measurements turned out to be unreliable because flow was measured in one of the portal vein's branches.

MRI measurements of portal venous flow were performed in 28 patients but not in 27 patients; inadequate breath-hold further disqualified 4 patients of interpretation.

Consequently, flow comparison of the portal vein could be made in 33 cases with respect to preoperative DDUS and perioperative DDUS; in 21 cases a comparison between preoperative DDUS and preoperative MRI was possible.

3.1.2. Hepatic artery measurements

During surgery, DDUS flow measurement of the hepatic artery could be performed in 46 patients and failed in 9 patients. Unreliable measurements were observed due to coexistence of multiple hepatic arteries ($n = 3$), mistakenly measuring maximum velocity instead of its mean ($n = 1$), wrong measurement timing (after colonic resection: $n = 1$).

The hepatic arterial flow was quantified by DDUS presurgically in 41 patients, whereas in 14 patients assessment was not possible for reasons discussed above. Existence of plural hepatic arteries

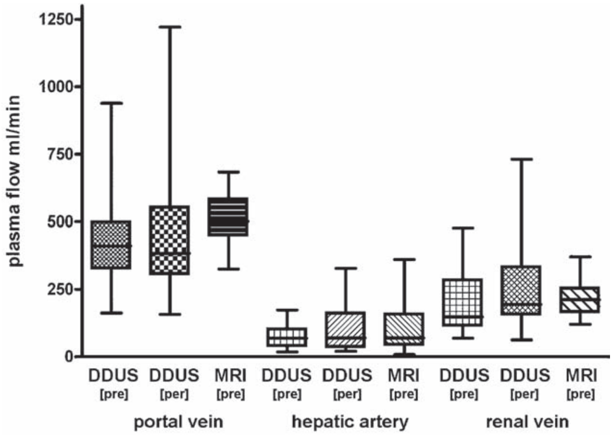

Fig. 1. Plasma flow in ml/min in the portal vein, hepatic artery and renal vein. Boxes show range and median for perioperative and preoperative DDUS as well as for preoperative MRI measurements. DDUS, DD ultrasound; [per], perioperative, [pre]; preoperative.

was observed in 3 patients disallowing inclusion of those measurements.

Presurgical hepatic artery flow assessment using MRI could be performed in 23 patients. Again, 3 of the 23 patients' measurements were excluded due to hepatic artery anatomic anomaly.

Consequently, hepatic artery flow could be compared in 32 cases for the preoperative DDUS and perioperative DDUS. In 11 cases a comparison between preoperative DDUS and preoperative MRI was possible.

3.1.3. *Renal vein measurements*

During surgery, flow in the renal vein was quantified by DDUS in 42 patients, whereas in 11 patients assessment was not possible. Eventually measurements of 2 patients had to be excluded due to invalidity.

Renal venous flow measurement prior to surgery by DDUS could be performed in 36 patients In 19 patients measurements were not possible for reasons mentioned earlier. Altogether 2 measurements were observed being unreliable.

In 27 patients the flow in the renal vein was assessed before surgery using MRI; in 28 patients, MRI renal flow quantification was not successful. In 1 patient the measurement was retrospectively qualified unreliable.

Flow in the renal vein could be compared in 32 cases for the preoperative DDUS and perioperative DDUS. In 21 cases a comparison between preoperative DDUS and preoperative MRI was possible.

3.2. *Flow in the portal vein*

Mean flow values are summarized in Table 2, flow value distribution is shown in Fig. 1.

Perioperative DDUS plasma flow measurements did not correlate with preoperative DDUS measurements ($r = 0.262$, $p = 0.142$). Equally, no significant correlation was observed between preoperative DDUS measurements and preoperative MRI measurements ($r = 0.360$, $p = 0.109$).

Exchangeability was assessed using the Bland–Altman plot, displaying the difference between both methods (ml/min) at each mean plasma flow. Fig. 2a shows the Bland–Altman plot for preoperative DDUS and perioperative DDUS. The pattern shown by this figure does not indicate any source of systematic error. The difference between both methods did not increase parallel with mean flow. A mean difference of −25 ± 202 ml/min was calculated, placing the limits of agreement at 378 and −428 ml/min.

Fig. 2b shows the Bland–Altman plot for the preoperative DDUS and the preoperative MRI. Again no systematic source of error was found and the difference between both techniques did not increase parallel with mean flow. A mean difference of −113 ± 140 ml/min was found. The limits of agreement were therefore set at 168 and −393 ml/min.

The paired *T*-test did not express significant differences between setting (preoperative and perioperative DDUS) however, significant differences between preoperative DDUS and preoperative MRI ($p = 0.001$) were detected.

When analyzing the variance, homogeneity was just not violated ($p = 0.050$). ANOVA indicated equality of means ($p = 0.117$).

3.3. *Flow in the hepatic artery*

Mean flow values are summarized in Table 2, flow value distribution is shown in Fig. 1.

A significant correlation was found for plasma flow measured by preoperative DDUS and perioperative DDUS ($r = 0.50$, $p = 0.004$). Likewise, a correlation was found between preoperative DDUS and preoperative MRI ($r = 0.64$, $p = 0.033$).

Subsequently, exchangeability was assessed using the Bland–Altman plots. Fig. 3a shows the Bland–Altman plot for preoperative DDUS and perioperative DDUS. The patterns show a uniformly spread distribution, which does not indicate any source of systematic error. The difference between both techniques did not seem to depend on mean plasma flow. A mean difference of −19 ± 58 ml/min was found, placing the limits of agreement at 96 and −135 ml/min.

As shown in Fig. 3b no systematic error could be detected concerning preoperative DDUS and preoperative MRI assessment. A mean difference of −20 ± 81 ml/min was calculated, therefore limits of agreement were set at 143 and −183 ml/min.

The paired *T*-test expressed no significant differences between preoperative and preoperative DDUS, and between preoperative DDUS and preoperative MRI.

When analyzing the variance, homogeneity was violated ($p = 0.001$). Welch Test indicated equality of means ($p = 0.130$).

3.4. *Flow in the renal vein*

Mean flow values are summarized in Table 2, flow value distribution is shown in Fig. 1.

When comparing the plasma flow values for the renal vein with respect to DDUS, no significant correlations were observed ($r = -0.76$, $p = 0.678$). Likewise the correlation between preoperative DDUS and the perioperative MRI was not significant ($r = 0.316$, $p = 0.152$).

The Bland–Altman plot in Fig. 4a shows the preoperative DDUS and perioperative DDUS. The pattern shows no signs of systematic error, although the difference seems to increase slightly when the mean plasma flow rises. A mean difference of −48 ± 177 ml/min was calculated; hence the limits of agreement were calculated between 305 and −401 ml/min.

Fig. 4b shows the Bland–Altman plot which assesses the difference between preoperative DDUS and preoperative MRI. No sources of systematic errors or increases in parallel with mean plasma flow are displayed. A mean difference of 2 ± 123 ml/min was calculated, which places the limits of agreement at 244 and −247 ml/min.

The paired *T*-test expressed no significant differences between preoperative and preoperative DDUS, and between preoperative DDUS and preoperative MRI.

When analyzing the variance, homogeneity was violated ($p = 0.013$). Welch Test indicated equality of means ($p = 0.282$).

Table 2
Mean plasma flow.

	Perioperative DDUS	Preoperative DDUS	Preoperative MRI
Portal Vein	433 ± 200 $n = 43$	423 ± 162[*] $n = 44$	507 ± 96[*] $n = 24$
Hepatic Artery	96 ± 70 $n = 41$	74 ± 41 $n = 38$	108 ± 91 $n = 16$
Renal Vein	248 ± 139 $n = 42$	201 ± 118 $n = 34$	219 ± 69 $n = 23$

Mean plasma flow measured preoperatively by DDUS and by MRI and perioperatively by DDUS. Data are expressed in mean ± SD in ml/min.

[*] Data differ significantly at the $p < 0.05$ level.

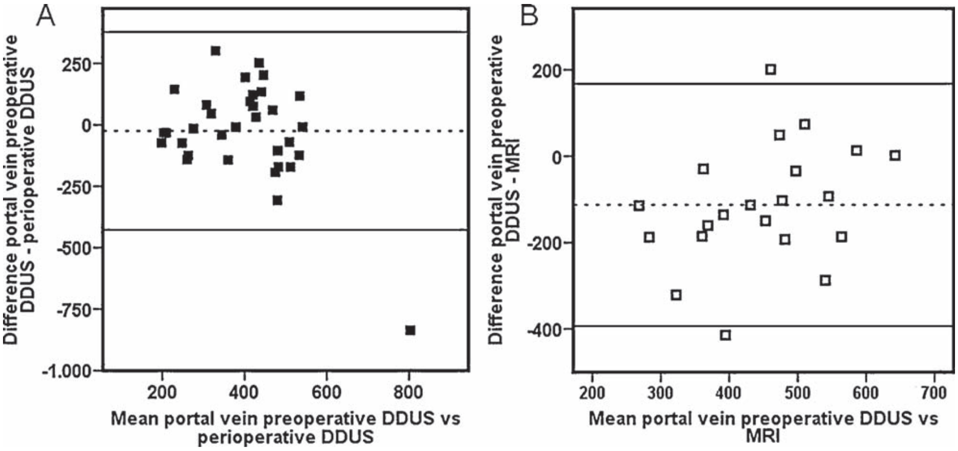

Fig. 2. Bland–Altman plot for the portal venous flow showing mean difference and mean ± 2SD. (A) Mean difference between perioperatively and preoperatively measured flow by DDUS is −25 ± 202 ml/min and limits of agreement are set at 378 and −428 ml/min. (B) Mean difference measured by preoperative DDUS and MRI. Mean difference is −113 ± 140 ml/min and limits of agreement are set at 168 and −393 ml/min.

4. Discussion

In the present study, we compared DDUS with MRI in the context of measuring blood flow in the hepatic and renal artery and the portal vein by a two-step approach: first, we were the first to evaluate the effect of surgery and anaesthesia on blood flow of the hepatic and renal artery and the portal vein, by DDUS. Then, we compared the preoperative DDUS results with MRI also performed before surgery.

We observed no significant differences between the different settings of DDUS measurement for all vessels. As for MRI however, portal flow differed from preoperative DDUS. When comparing all measurements per vessel, no differences in means were observed.

However, absence of correlation in the setting (perioperative DDUS vs. preoperative DDUS) and method (preoperative DDUS vs. preoperative MRI) were observed. Individually, widespread margins in the Bland Altman agreement plots were calculated.

4.1. Perioperative vs. preoperative measurements

In our study the perioperative DDUS was considered as a reference standard, because this technique measured plasma flow in

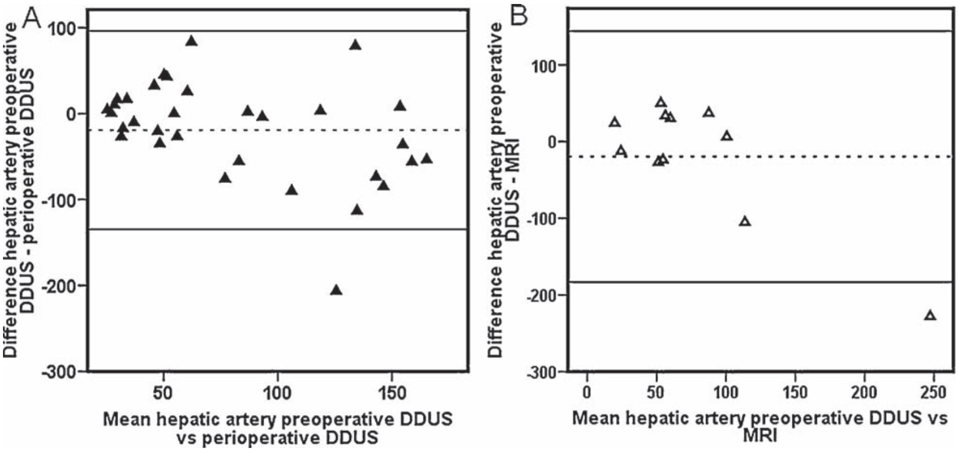

Fig. 3. Bland–Altman plot for the hepatic artery showing mean and mean ± 2SD. Mean difference between preoperatively and perioperatively measured DDUS (A) is −19 ± 58 ml/min and limits of agreement are set at 96 and −135 ml/min. Mean difference between preoperatively performed DDUS and MRI (B) is −20 ± 81 ml/min and limits of agreement were calculated as 143 and −183 ml/min.

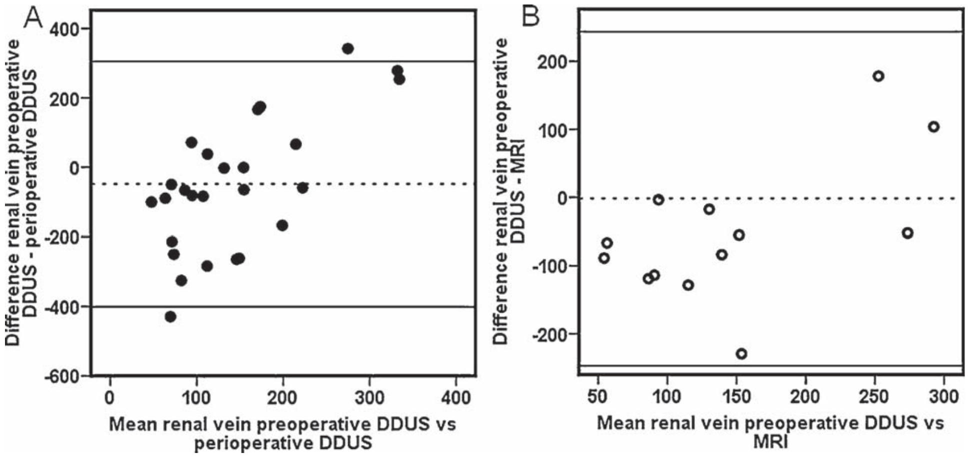

Fig. 4. Bland–Altman plot illustrating mean difference and mean ± 2SD for renal venous flow as measured by perioperatively and preoperatively performed DDUS (A). Mean difference is −48 ± 177 ml/min and limits of agreement are set at 305 and −401 ml/min. Mean difference between preoperatively performed DDUS and MRI (B) is 2 ± 123 ml/min and limits of agreement were calculated 244 and −247 ml/min.

the exact setting in which we intended to analyze plasma concentrations for flux rate calculations. Furthermore measuring directly onto the vessel, which is allowed by perioperative DDUS, theoretically best estimates the angle of insonation, theoretically enabling more accurate flow measurement.

Remarkably, this seems to contrast the observed wide range and standard deviation of perioperative DDUS measurements (Table 2 and Fig. 1). Perioperative DDUS portal and renal venous measurement showed the highest variability. Taken into account that the only correlations were found for hepatic artery measurements, this could imply that either perioperative portal and renal vein measurements are more difficult to perform accurately, or surgery induces an unpredictable effect on flow in the portal and the renal vein. Interestingly, the muscular anatomy of the arterial wall would naturally be more prone to be influenced by anesthetics and surgical stress, suggesting a wider range should theoretically have occurred for hepatic artery data, which was not the case.

In almost all subjects the overall effect of surgery (comparing DDUS pre- and perioperatively) was not identified systematically in the same direction.

Eventually, when assessing whether mean preoperative and perioperative measurements differ, we did not notice statistical significance, suggesting that mean DDUS – whether during or before surgery – is exchangeable.

4.2. DDUS and MRI measurements

Preoperative portal flow measurement by MRI and DDUS did produce different results when MRI instead of DDUS was used. This did not occur in comparing hepatic arterial flow and renal venous flow measurement with these two methods. Pearson correlation test shows the strongest relation for the hepatic artery. The correlations observed when evaluating the portal venous measurement were not significant although most results did show trends towards significance. Considering renal venous flow, correlations were not significant suggesting that individual flow measurements for this vein are not per se interchangeable.

Although DDUS is a widely used technique for non invasive measurement of blood flow in abdominal and non-abdominal vessels with the advantage that it can be used repeatedly, it has its limitations [11,13,14]. Disadvantages include the estimation of the angle of insonation, the difficulty in determining the cross-sectional area of the vessels and the high inter-observer variability [11,13]. Since MRI already proved to be an alternative method for measuring flow in abdominal and non-abdominal vessels [2,7–10,17,18], it might in fact be a more accurate technique of flow measurement as a result of the minor inter-observer variability, in comparison with DDUS measurement [11,19]. Additionally, MRI flow measurement can be performed without being hindered by bowel gasses or patient habitus [9]. This is partly in agreement with our observations as reflected by the display of the range in MRI results in Fig. 1 for portal and renal venous flow and by calculated unequal variances for renal venous flow.

The absence of a gold standard method makes a true comparison between both methods difficult. Whereas the use of microspheres for flow measurement in animals is used as the standard method, this technique is not suitable for human use. Nevertheless, previous research conducted by Nijeholt et al. demonstrates that MRI is preferred for absolute flow evaluation rather than DDUS. As a reference standard total liver blood flow was calculated and compared with reference values for hepatic blood flow, obtained by previous studies measuring indocyanine and D-sorbitol clearance [20,21]. In this particular study a correlation between portal flow measured by MRI and DDUS was observed even though the study was limited to 8 healthy volunteers [9]. In contrast, Nanashima et al. evaluated MRI and DDUS flow measurements in the portal and hepatic vein in 75 consecutive patients and did not observe any correlation between both methods [2].

In order to create a reference standard for perioperative flow, metabolic studies using stable isotopes could prove useful. This could be executed by comparing flow dependent flux calculations with independent whole body rate of appearance values. Alternatively hepatic clearance could serve as a particular reference standard in the MRI/DDUS comparison when evaluating hepatic blood flow. Unfortunately, since we are the first to have evaluated renal plasma DDUS with MRI, we have no comparative work to discuss here. However, renal clearance could prove a good candidate to assist the MRI/DDUS comparison for renal blood flow.

4.3. Bland–Altman plots

The Bland–Altman plot is nowadays regarded as a very accurate method of assessing interchangeability of two methods. The alternative often used for exchangeability assessment, the Pearson correlation test, can be misleading since the correlation coefficient *r* represents the strength of the correlation, but not the agreement.

The Bland–Altman plots that were made in order to assess exchangeability did not show any source of systematic error. Overall, no increase in difference was observed parallel with the increase in mean plasma flow, although this might be disputable for renal venous flow measurement by DDUS (Fig. 4b). The limits of agreement reflect reliability by transforming the standard deviation (more precisely 2SD) into a concrete margin of agreement. Considering the magnitude of the error, the Bland–Altman plots reached moderately wide levels of agreement implying large variation. Conclusively, although interchangeability is legitimate (absence of errors), it adds a significant variance to the measured plasma flow.

5. Conclusion

In summary, considering both the absent or marginal correlations individually, as well as the widespread margins in the Bland–Altman agreement plots, we do not recommend individual flow assessment. Since no differences were observed when assessing means it can be reasoned that mean values are in fact interchangeable. Since it can be theorized that MRI would be a more reliable method for measuring absolute flow, we therefore suggest that mean values for flow assessment of the hepatic and renal artery and the portal vein may be performed in the preoperative MRI setting, when perioperative flow indication is necessary for metabolic quantification.

Conflict of interest

None declared.

Acknowledgements

We would like to thank Erwin Kist and Lloyd Belliot for their help with the MRI and DDUS measurements.

References

[1] Korperich H, Gieseke J, Barth P, Hoogeveen R, Esdom H, Peterschroder A, et al. Flow volume and shunt quantification in pediatric congenital heart disease by real-time magnetic resonance velocity mapping: a validation study. Circulation 2004;109(16):1987–93.
[2] Nanashima A, Shibasaki S, Sakamoto I, Sueyoshi E, Sumida Y, Abo T, et al. Clinical evaluation of magnetic resonance imaging flowmetry of portal and hepatic veins in patients following hepatectomy. Liver Int 2006;26(5):587–94.
[3] Powell AJ, Geva T. Blood flow measurement by magnetic resonance imaging in congenital heart disease. Pediatr Cardiol 2000;21(1):47–58.
[4] Tahmasebpour HR, Buckley AR, Cooperberg PL, Fix CH. Sonographic examination of the carotid arteries. Radiographics 2005;25(6):1561–75.
[5] Ligthart-Melis GC, van de Poll MC, Vermeulen MA, Boelens PG, van den Tol MP, van Schaik C, et al. Enteral administration of alanyl-[2-(15)N]glutamine contributes more to the de novo synthesis of arginine than does intravenous infusion of the dipeptide in humans. Am J Clin Nutr 2009;90(1):95–105.
[6] Siroen MP, Van dS Jr, Teerlink T, Van Schaik C, Nijveldt RJ, van Leeuwen PA. The human liver clears both asymmetric and symmetric dimethylarginine. Hepatology 2005;41(3):559–65.
[7] Klein C, Schalla S, Schnackenburg B, Bornstedt A, Fleck E, Nagel E. Magnetic resonance flow measurements in real time: comparison with a standard gradient-echo technique. J Magn Reson Imaging 2001;14(3):306–10.
[8] Rebergen SA, van der Wall EE, Doornbos J, de Roos A. Magnetic resonance measurement of velocity and flow: technique, validation, and cardiovascular applications. Am Heart J 1993;126(6):1439–56.
[9] Nijeholt GJ, Burggraaf K, Wasser MN, Schultze Kool LJ, Schoemaker RC, Cohen AF, et al. Variability of splanchnic blood flow measurements using MR velocity mapping under fasting and post-prandial conditions—comparison with echo-Doppler. J Hepatol 1997;26(2):298–304.
[10] Powell AJ, Chung T, Landzberg MJ, Geva T. Accuracy of MRI evaluation of pulmonary blood supply in patients with complex pulmonary stenosis or atresia. Int J Card Imaging 2000;16(3):169–74.
[11] de Vries PJ, van Hattum J, Hoekstra JB, de Hooge P. Duplex Doppler measurements of portal venous flow in normal subjects. Inter- and intra-observer variability. J Hepatol 1991;13(3):358–63.
[12] Yzet T, Bouzerar R, Allart JD, Demuynck F, Legallais C, Robert B, et al. Hepatic vascular flow measurements by phase contrast MRI and doppler echography: a comparative and reproducibility study. J Magn Reson Imaging 2010;31(3):579–88.
[13] Gill RW. Measurement of blood flow by ultrasound: accuracy and sources of error. Ultrasound Med Biol 1985;11(4):625–41.
[14] Brown HS, Halliwell M, Qamar M, Read AE, Evans JM, Wells PN. Measurement of normal portal venous blood flow by Doppler ultrasound. Gut 1989;30(4):503–9.
[15] Debatin JF. MR quantification of flow in abdominal vessels. Abdom Imaging 1998;23(5):485–95.
[16] Bongartz GM, Boos M, Winter K, Ott H, Scheffler K, Steinbrich W. Clinical utility of contrast-enhanced MR angiography. Eur Radiol 1997;7(Suppl. 5):178–86.
[17] Tamada T, Moriyasu F, Ono S, Schimizu K, Kajimura K, Soh Y, et al. Portal blood flow: measurement with MR imaging. Radiology 1989;173(3):639–44.
[18] Firmin DN, Nayler GL, Klipstein RH, Underwood SR, Rees RS, Longmore DB. In vivo validation of MR velocity imaging. J Comput Assist Tomogr 1987;11(5):751–6.
[19] Paulson EK, Kliewer MA, Frederick MG, Keogan MT, Delong DM, Nelson RC. Doppler US measurement of portal venous flow: variability in healthy fasting volunteers. Radiology 1997;202(3):721–4.
[20] Molino G, Cavanna A, Avagnina P, Ballare M, Torchio M. Hepatic clearance of D-sorbitol. Noninvasive test for evaluating functional liver plasma flow. Dig Dis Sci 1987;32(7):753–8.
[21] Soons PA, De Boer A, Cohen AF, Breimer DD. Assessment of hepatic blood flow in healthy subjects by continuous infusion of indocyanine green. Br J Clin Pharmacol 1991;32(6):697–704.