



Low hepatic artery resistive index on Doppler ultrasound performed on the first post-liver transplant day is associated both with hepatic artery thrombosis and decreased graft survival

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Abstract

Purpose Although liver transplantation (LT) outcomes have improved significantly over the last decades, early vascular complications are still associated with elevated risks of graft failure. Doppler ultrasound (DUS) enables detection of vascular complications, provides hepatic artery Resistive Index (RI). The aim of our study was to evaluate the association of the RI parameters of DUS performed in the first post-transplant week with post-transplant outcomes.

Methods All consecutive patients undergoing a first LT between 2001 and 2019 at a single center were included. Patients were divided into two groups: $RI < 0.55$ and $RI \geq 0.55$. Patients were also divided according to the presence or absence of hepatic artery thrombosis (HAT). Graft survival was compared between groups.

Results Overall, 338 patients were included. HAT occurred in 23 patients (6.8%), of which 7 were partial and 16, complete. Biliary complications were more common in patients with HAT (10 [43.5%] vs. 38 [12.1%] [$p < 0.001$]). Graft survival was lower for patients with HAT ($p = 0.047$). Also, $RI < 0.55$ was associated with increased incidence of HAT ($p < 0.001$). Additionally, patients with $RI < 0.55$ on post-operative day 1 had decreased graft survival as compared to patients with $RI > 0.55$ ($p = 0.041$). RI on post-operative day 3 and 5 was not predictive of inferior graft outcomes.

Conclusions Intensive use of DUS in the early post-LT period offers the possibility of early diagnosis of vascular complications, guiding medical and surgical management of HAT. Additionally, according to our data, low RI (< 0.55) on the first postoperative day also is a predictor of HAT and decreased graft-survival.

Keywords Liver transplant · Hepatic artery thrombosis · Doppler ultrasound · Arterial resistive index

Abbreviations

HAT Acute hepatic artery thrombosis
DUS Doppler ultrasound
LT Liver transplantation
RI Resistive Index

Introduction

Although liver transplantation (LT) outcomes have improved significantly over the last decades, early post-transplant vascular complications are still associated with an elevated risk of graft failure [1, 2]. The most frequent vascular complication after LT is hepatic artery thrombosis (HAT) [3, 4].

The liver is a unique organ because it has a dual blood supply, via the hepatic artery and the portal vein. However, in the early postoperative period, the support provided by collateral blood vessels is still insufficient. Thus, whenever early acute HAT occurs, severe ischemic injury ensues, which can culminate in graft loss. HAT occurs in 3–9% of all liver transplants and is classified as early acute HAT when it is identified in the first 30 post-transplant days [2, 3, 5, 6].

There are some options for the treatment of early acute HAT, which include surgical revascularization

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Table 1 Clinical and demographic characteristics of the entire cohort

	Total
Pre-operative Variables	
Age (years), median [IQR]	57 [48–62]
Male gender, n (%)	206 (60.9)
BMI, median [IQR]	30.6 [25.9–42.7]
HCV Infection, n (%)	215 (63.6)
HCC, n (%)	162 (47.9)
MELD score, median [IQR]	15 [10–21]
Chemoembolization, n (%)	78 (23%)
Intraoperative Variables	
Bleeding (ml), median [IQR]	2582 [1544–4149]
Red Blood Cell (RBC) transfusion (units), median [IQR]	2 [0–4]
Cell Saver Usage, n (%)	163 (48.2)
Cold ischemia time (min), mean \pm SD	458.8 \pm 110
Interval between venous and arterial reperfusion (min), median [IQR]	51.5 [40–74]
Post-operative Outcomes	
Hepatic Artery Thrombosis, n (%)	23 (6.8)
Biliary complications, n (%)	48 (14.2)

(thrombectomy, redo anastomosis, or thrombolysis), with a success rate ranging from 10 to 50%, and ultimately retransplantation [4, 7, 8]. Doppler Ultrasound (DUS) is routinely performed in the first post-transplant week with the goal of early detection of vascular complications, and prevent graft loss [3, 9]. Early diagnosis of HAT is the only way of enabling treatment that may offer a chance of saving the allograft [3].

DUS is a non-invasive, semi-quantitative method capable of detecting vascular abnormalities by estimating the resistance to arterial blood flow, quantified as the Resistive Index (RI). Despite DUS widespread utilization around the world, few studies have investigated the role of the RI as a surrogate

marker of vascular complications and graft outcomes. Thus, the aim of our study was to evaluate the association of the RI parameters of DUS performed in the first post-transplant week with post-transplant outcomes.

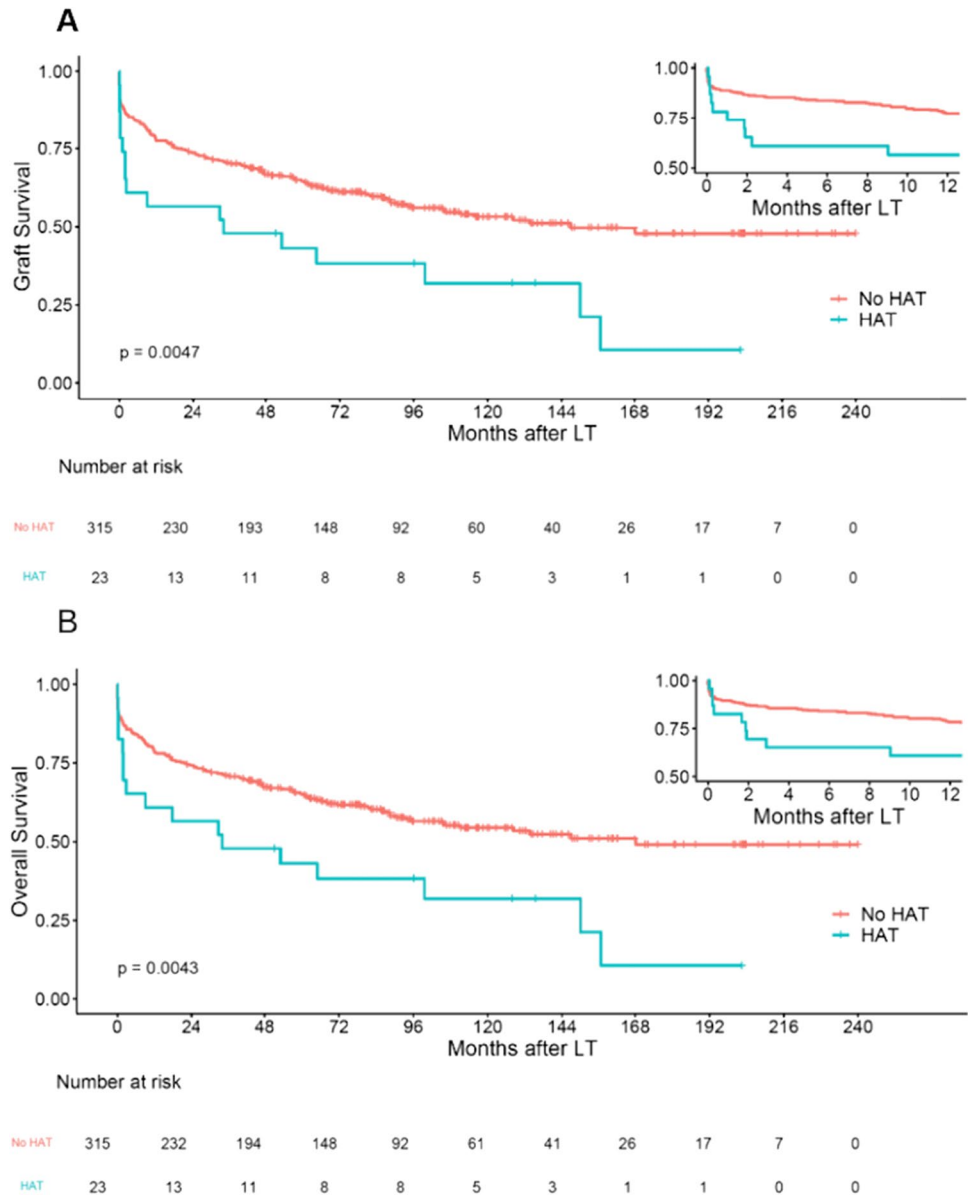
Patients and methods

All consecutive adult patients (age > 18 years) who received a first liver transplant from 2001 to 2019 at the Hospital de Clínicas de Porto Alegre (HCPA) were included. Data was extracted from a prospective database. Pediatric recipients (age < 18 years), recipients of partial grafts (split livers and

Table 2 Comparison of demographic variables of patients with HAT ($n=23$) vs. without HAT ($n=315$)

	No Thrombosis	Thrombosis	<i>p</i>
Age (years), median [IQR]	57 [47.5–62]	58 [54–62]	0.303
Male gender, n (%)	193 (61.3)	13 (56.5)	0.819
HCV Infection, n (%)	200 (63.5)	15 (65.2)	> 0.999
Bleeding (ml), median [IQR]	2582 [1577– 4185]	2505 [1139–3693]	0.394
RBC transfusion (units), median [IQR]	2 [0–4]	[0–2]	0.108
MELD score, median [IQR]	15 [10–21]	13 [9–14]	0.027
BMI, median [IQR]	30.6 [26 – 42.8]	29.6 [23.6 – 49.7]	0.269
Cold ischemia time (min), mean \pm SD	457.5 \pm 109	475.5 \pm 123.1	0.571
Interval between venous and arterial reperfusion (min), median [IQR]	50 [40–70]	72.5 [43.5–97]	0.022
HCC, n (%)	151 (47.9)	11 (47.8)	> 0.999
Biliary complications, n (%)	38 (12.1)	10 (43.5)	< 0.001
Cell Saver Usage, n (%)	152 (48.3)	11 (47.8)	> 0.999
Chemoembolization, n (%)	70 (22.2)	8 (34.8)	0.261

Fig. 1 **A)** Graft survival according to the presence or absence of HAT ($p=0.0047$). **B)** Overall patient survival according to the presence or absence of HAT ($p=0.043$)



living donor grafts), and patients who received simultaneous transplants (liver and kidney) were excluded.

Post-transplant DUS examinations were performed by a dedicated team of radiologists. In most examinations, a Philips HD15 ultrasound scanner was used, with a convex probe and a frequency of 2–5 MHz. The peak systolic velocity and end diastolic velocity of the hepatic artery were checked at the hilum, distal to the hepatic artery anastomosis. The RI was calculated as follows: (peak systolic velocity – end diastolic velocity) / (peak systolic velocity). The DUS was performed immediately post-LT, 1st and 7th days after LT in the first 80 transplants included in this analysis. Since 2006, our aim has been to perform DUS on the 1st, 3rd, 5th and 7th post-transplant days. Patients who had DUS performed on 1st, 3rd and 5th post-transplant days

were included in this analysis. According to the result of the RI performed on the 1st post-LT day, the patients were divided into two groups: those with $RI < 0.55$ and $RI \geq 0.55$, according to a recent study published by Gaspari et al. [10].

The diagnostic confirmation of HAT was performed by CT angiogram in all cases. Partial thrombosis was defined as either incomplete thrombosis of the main hepatic artery or complete thrombosis of one of the lobar (right or left) hepatic arteries based on CT angiogram findings. Patients who developed early HAT were not included in RI DUS analyses of subsequent days. The treatment of partial thrombosis was based on systemic anticoagulation with intravenous heparin with a goal of activated thromboplastin time between 1.5 and 2.5. Daily DUS was performed on those patients. After discharge from the ICU to the surgical floor

Table 3 Incidence of HAT stratified by RI groups (<0.55 vs. ≥0.55) on the first, third and fifth posttransplant days

	Hepatic Arterial Thrombosis		<i>p</i>
	No	Yes	
	n (%)	n (%)	
RI 1st post-transplant day			
<0.55	54 (80.6%)	13 (19.4%)	<0.001
≥0.55	235 (96.3%)	9 (3.7%)	
RI 3rd post-transplant day			
<0.55	30 (96.8%)	1 (3.2%)	>0.999
≥0.55	195 (99%)	2 (1%)	
RI 5th pos-transplant day			
<0.55	30 (100%)	0 (0%)	>0.999
≥0.55	195 (99%)	2 (1%)	

Chi-square test

RI: Resistive Index

(usually 48 to 72 h after they were started on IV heparin), patients were transitioned to subcutaneous heparin or salicylic acid 100 mg daily. In addition to the anticoagulation protocol, all patients with total thrombosis were enlisted for retransplantation, and surgical revascularization was attempted whenever HAT was detected before significant graft dysfunction occurred.

The primary study outcome was graft survival according to the category of RI (<0.55 or ≥0.55) and to the presence or absence of HAT. Secondary outcomes were overall patient survival, biliary complications and cause of graft loss.

Categorical variables were represented by the absolute and relative frequency and compared using Chi-square test. Normality test of continuous variables was estimated through the Shapiro–Wilk test. Continuous variables were represented by the median and the interquartile range (P50 [25; P75]) or by the mean and standard deviation and were compared using the Mann–Whitney test or Student's *t*-test as appropriate. Graft survival, overall patient survival and cumulative incidence of biliary complications were estimated via the Kaplan–Meier method. Univariate analysis using Cox proportional hazard's regression was performed to identify predictors of graft survival. Variables with *p*-value <0.05 on univariate analysis were pulled into multivariate analysis. For all analyses, a *p*-value <0.05 was considered as statistically significant. Statistical analysis was performed using R for MacOS version 4.0.3 [11].

Results

A total of 338 patients who underwent a first LT were eligible for the study. Of these, 206 (60.9%) were males. The median age was 57 (IQR: 48–62) years. Hepatitis C virus

(HCV) infection was present in 215 patients (63.6%). The median calculated MELD score was 15 (IQR: 10–21). Hepatocellular carcinoma (HCC) was present in 162 (47.9%) patients. (Table 1). HAT incidence was 6.8% (23/338).

Table 2 demonstrates a comparison between patients who developed HAT (*n* = 23) and those who did not have HAT (*n* = 315). Patients who had HAT had a lower calculated MELD score than those without HAT (median of 13 [IQR: 9.5 – 14.5] vs. 15 [IQR = 10–21]) (*p* = 0.027). Additionally, the interval between venous and arterial reperfusion was higher among those who had HAT compared to those without HAT (median of 72.5 min [IQR 43.5–97] vs. 50 min [40 – 70]) (*p* = 0.022). Biliary complications were also more common in patients with HAT (10 [43.5%]) vs. 38 [12.1%]) (*p* < 0.001). For all other variables, there was no significant statistical difference between the two groups.

Of the total 23 thromboses (incidence of 6.8% for the entire cohort), 16 (69.6%) were complete and 7 (30.4%) were partial. Twelve thromboses (52.2%) were diagnosed on ultrasound performed within the first 24 h (1st post-transplant day), 8 (34.8%) were diagnosed on ultrasound on the 3rd post-transplant day, 2 (8.7%) were diagnosed between the 4th and 7th post-transplant day, and 1 (4.3%) on the 29th post-transplant day.

All attempts for revascularization (endovascular or surgical) occurred within a time frame of 3 to 12 h after the diagnosis of HAT. Two out of seven patients with partial thrombosis also received a transcatheter endovascular intervention with intra-arterial alteplase with or without stent placement, being placed on IV heparin as well. Only one patient (14.2%) with partial thrombosis experienced graft loss.

In the first 30 post-transplant days. As for patients with complete thrombosis, 12 underwent surgical revascularization (arterial thrombectomy with intra-arterial alteplase and redo of arterial anastomosis with or without creation of an arterial conduit). In total, there were 3 (18.7%) graft losses in the first 30 post-transplant days, 2 of which died and 1 underwent retransplantation.

Graft survival in those without HAT at 1-year, 3-years and 5-years was 77.4%, 70.4%, 64.6% respectively. Meanwhile, graft survival in those with HAT, survival rate at 1-year, 3-years and 5-years were: 56.5%, 47.8%, and 43% (*p* = 0.047) (Fig. 1).

For the DUS on the 1st post-transplant day, there were a total of 67 (19.8%) patients with RI <0.55 and 244 (72.2%) patients with RI ≥0.55. In 27 (8%) patients, DUS on 1st post-transplant day was unavailable. Thirteen (19.4%) patients with RI <0.55 on the 1st post-transplant day developed HAT, whereas 9 (3.6%) patients with RI ≥0.55 had HAT (Table 3). The difference was statistically significant (*p* < 0.001). The 1-year, 3-year and 5-year graft survival were, respectively, 70.1%, 62.6% and 54%

for RI < 0.55 vs. 81.1%, 73.7% and 68.5% for RI ≥ 0.55 ($p=0.041$). The Hazard ratio was 1.50 (95% CI= 1.01—2.21) for RI < 0.55 vs. RI ≥ 0.55 (Fig. 2).

For the DUS on the 3rd post-transplant day, there were a total of 33 (9.7%) patients with RI < 0.55 and 200 (59.2%) patients with RI ≥ 0.55. In 105 (31%), DUS on 3rd post-transplant day was unavailable. One (3.1%) patient with RI < 0.55 on the 3rd post-transplant day developed HAT on subsequent days, whereas 2 (1%) patients with RI ≥ 0.55 had HAT ($p=0.879$) (Table 3). The 1-year, 3-year and 5-year graft survival were, respectively, 78.8%, 66.7% and 63.2% for RI < 0.55 vs. 84.5%, 77% and 70.4% for RI ≥ 0.55 ($p=0.36$). The Hazard ratio was 1.3 (95% CI=0.74 – 2.26,) for RI < 0.55 vs. RI ≥ 0.55 (Figs. 2 and 3).

On the 5th post-transplant day DUS, there were a total of 26 (7.7%) patients with RI < 0.55 and 206 (61%) patients with RI ≥ 0.55. In 106 (31.3%), DUS on 5th post-transplant day

was unavailable. No patient with RI < 0.55 on the 5th post-transplant day developed HAT on subsequent days, whereas 2 (1%) patients with RI ≥ 0.55 had HAT ($p>0.99$) (Table 3). The 1-year, 3-year and 5-year graft survival were, respectively, 76.9%, 69.2%, 69.2% for RI < 0.55, vs. 85%, 77.6% and 69.5% for RI ≥ 0.55 ($p=0.15$) The Hazard ratio was 1.5 (95% CI=0.85 – 2.67) for RI < 0.55 vs. RI ≥ 0.55 (Fig. 4).

Table 4 shows the relationship between RI groups and the incidence of biliary complications. Comparing the rate of biliary complications between the RI groups (<0.55 vs. ≥0.55) no statistically significant difference was detected ($p=0.135$). However, a time-to-event analysis using the Kaplan Meier method was performed (Fig. 5) for RI groups on 1st post-transplant day. Patients with RI < 0.55 had higher cumulative incidence of biliary complications ($p=0.037$).

Tables 5 and 6 shows a Cox regression model to estimate the role of variables in relation to the outcome of

Fig. 2 A) Graft survival according to the RI group on 1st POD ($p=0.041$). B) Overall patient survival according to the RI group on 1st POD ($p=0.11$)

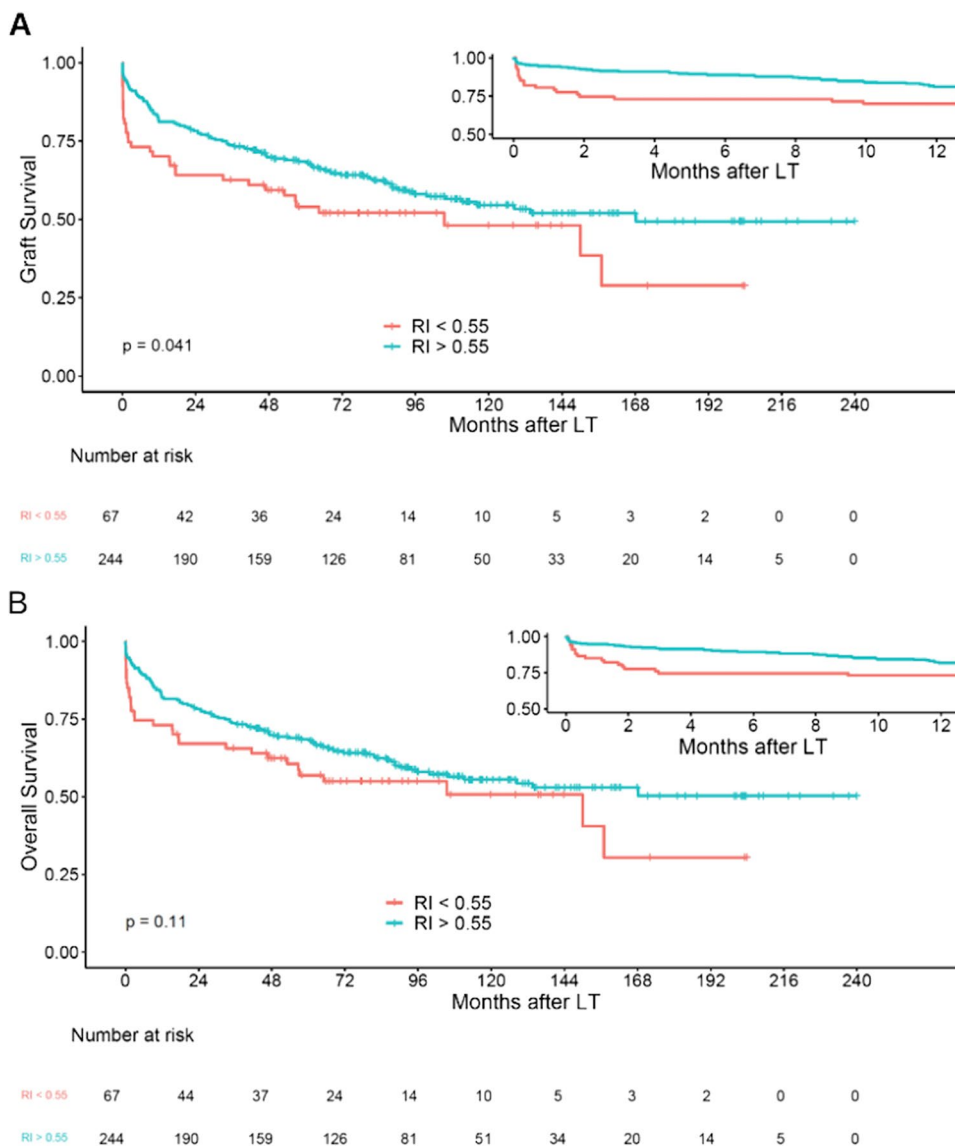
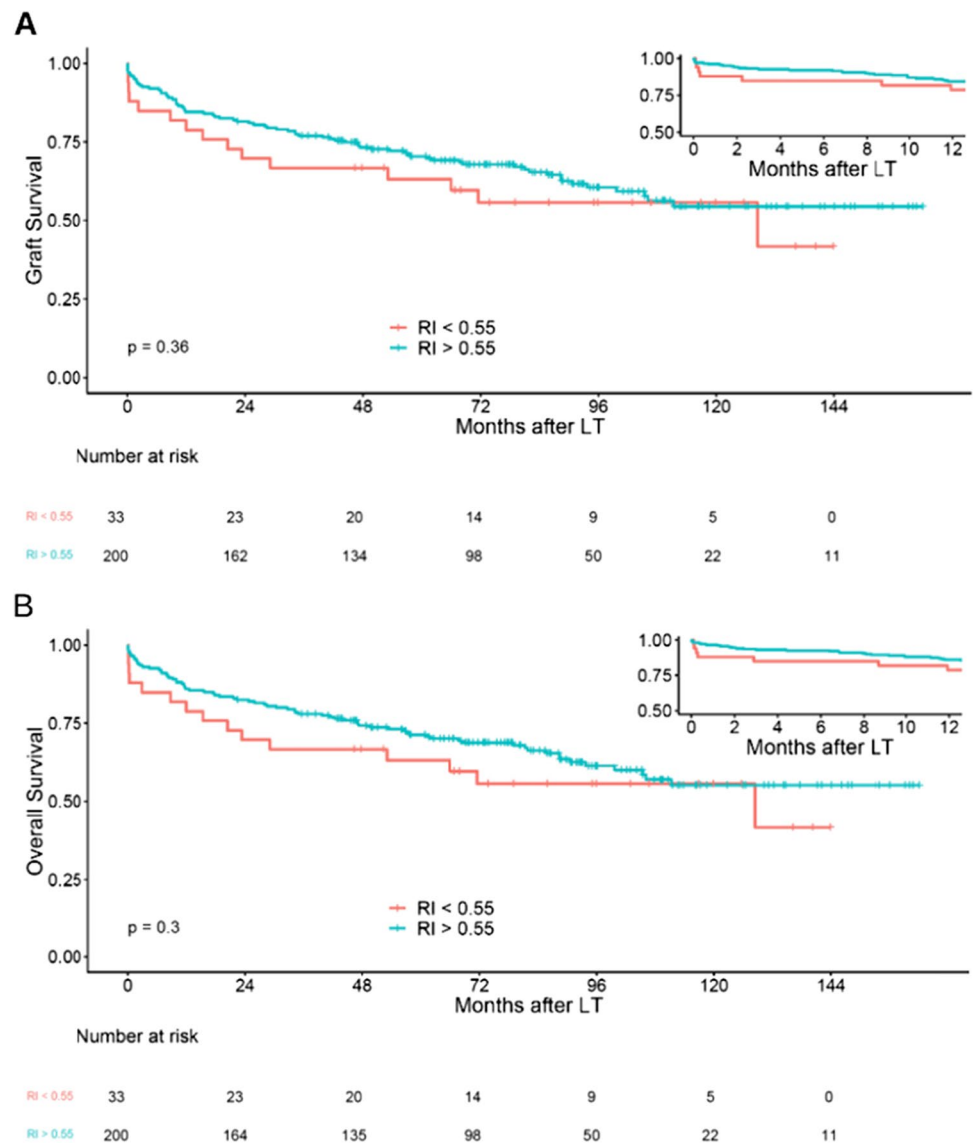


Fig. 3 **A)** Graft survival according to the RI group on 3rd POD ($p=0.36$). **B)** Overall patient survival according to the RI group on 3rd POD (0.3)



graft survival. In univariate analysis (Table 5), HAT with HR 2.036 [1.229 – 3.372] ($p=0.005$), bleeding (L) with HR 1.081 [1.03; 1.135] ($p=0.001$), RI < 0.55 on 1st post-transplant day with HR 1.497 [1.016, 2.209] ($p=0.041$) and interval between venous and arterial reperfusion (min) with HR 1.004 [1.001; 1.007] ($p=0.004$) all were associated with decreased graft. These variables were pulled into a multivariate model (Table 6) None of the variables remained significantly associate with graft survival in multivariate Cox regression.

Table 7 shows the cause of graft loss according to RI. Of the 67 patients with an RI < 0.55 on 1st post-transplant day, 34 (50.7%) patients experienced graft loss during the study period. In this group, primary nonfunction (11.8%), sepsis (14.7%) and miscellaneous causes (14.7%) were the most common causes of graft loss. Conversely, of the 244 patients with RI \geq 0.55 on 1st post-transplant day, 102

(41.8%) experienced graft loss during the study period. The most common cause of death was miscellaneous ($n=22$, 21.6%) and disease recurrence ($n=17$, 16.7%). No statistically significant difference in cause of death between the two groups was detected.

Discussion

DUS has been an important tool to diagnose early post-transplant vascular complications following LT [12]. Early identification of vascular complications in the post-transplant period implies the adoption of medical treatment (with systemic anticoagulation) or surgical (through surgical thrombectomy) aiming at saving the liver graft [8]. Whenever those treatments fail, early retransplantation is warranted. Given the importance of vascular evaluation

Fig. 4 **A)** Graft survival according to the RI group on 5th POD ($p=0.15$). **B)** Overall survival according to the RI group on 5th POD ($p=0.13$)

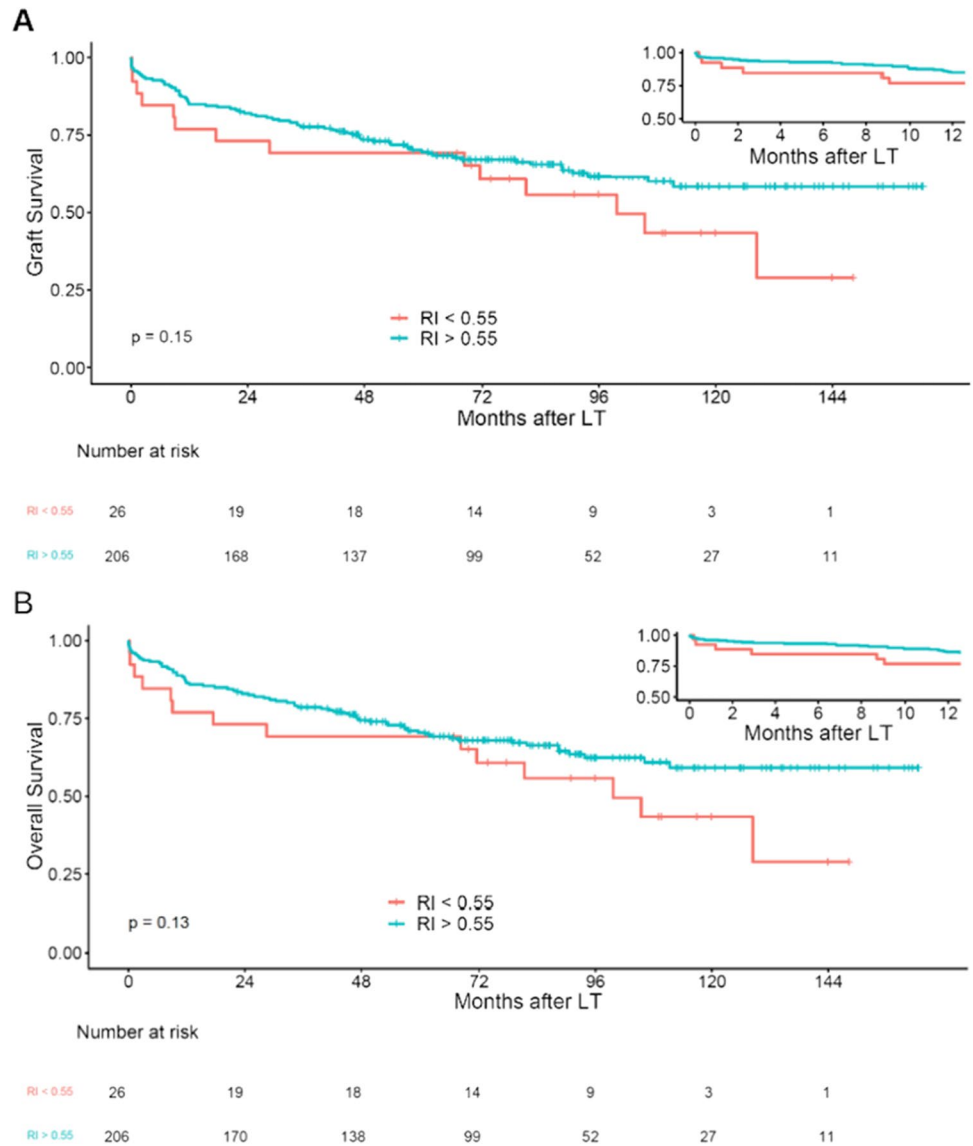


Table 4 Comparison of hepatic artery resistive index groups between patients with or without biliary complications

	Biliary complications		<i>p</i>
	No	Yes	
	n (%)	n (%)	
RI 1st post-transplant day			
<0.55	53 (79.1)	14 (20.9)	0.135
≥0.55	213 (87.3)	31 (12.7)	
RI 3rd post-transplant day			
<0.55	28 (84.8)	5 (15.2)	0.757
≥0.55	177 (88.5)	23 (11.5)	
RI 5th pos-transplant day			
<0.55	20 (76.9)	6 (23.1)	0.131
≥0.55	184 (89.3)	22 (10.7)	

Chi-square test
RI: Resistive Index

with DUS, most liver transplant centers, including ours, have used this tool routinely in the post-transplant period of transplanted patients. However, there is still no consensus in the literature as to what would be an adequate and safe RI, nor is there an agreement as to whether it impacts transplant results, especially in the long term. Moreover, the most appropriate post-transplant DUS protocol is yet to be determined [13, 14].

Our study included 344 patients who underwent LT, of which 23 (6.8%) developed HAT. Thrombosis was partial in 7 patients, who were treated with systemic anticoagulation and, in some cases, endovascular intervention. Among the patients with partial thrombosis, there was only 1 graft loss in the first 30 post-transplant days. Of the 16 patients with complete thrombosis, surgical revascularization was attempted in 12. Graft loss in the first 30 post-transplant days was observed in 3/16 patients (18.7%) with complete

Fig. 5 Cumulative incidence of biliary complications according to RI group on 1.st POD ($p=0.037$)

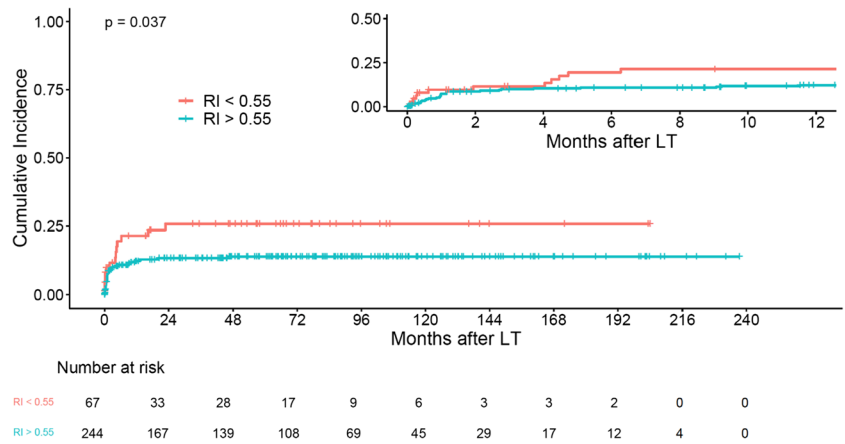


Table 5 Univariate analysis for Graft Survival of overall cohort of transplanted patients

	The Cox Regression		
	HR	[IC95%]	<i>p</i>
Male gender	0.986	[0.712; 1.365]	0.932
HCV Infection	0.977	[0.702; 1.358]	0.889
HCC	0.892	[0.548; 2.27]	0.483
HAT	2.036	[1.229; 3.372]	0.005
Biliary complications	0.796	[0.498; 1.275]	0.343
Cell Saver Usage	1.022	[0.742; 1.409]	0.891
Chemoembolization	0.919	[0.628; 1.347]	0.668
Age in Tx (years)	0.996	[0.9833; 1.011]	0.659
Bleeding (L)	1.081	[1.; 1.135]	0.001
RBC transfusion (units)	1.041	[1; 1.084]	0.05
MELD score	1.013	[0.995; 1.032]	0.144
BMI	1.018	[0.997; 1.038]	0.089
RI < 0.55 on 1st post-transplant day	1.497	[1.016; 2.209]	0.041
RI < 0.55 on 3rd post-transplant day	1.296	[0.744; 2.258]	0.361
RI < 0.55 on 5th post-transplant day	1.51	[0.852; 2.678]	0.158
Cold ischemia time (min)	1.000	[0.998; 1.003]	0.73
Interval between venous and arterial reperfusion (min)	1.004	[1.001; 1.007]	0.004

HCV: Hepatitis C Virus, HCC: Hepatocarcinoma, HAT: Hepatic Artery Thrombosis, BMI: Body Mass Index, RBC: Red Blood Cell

Table 6 Multivariate analysis for Graft Survival of overall cohort of transplanted patients

	The Cox Regression		
	HR	[IC95%]	<i>p</i>
Bleeding (L)	0.993	[0.893; 1.105]	0.352
HAT	1.796	[0.978; 3.299]	0.059
RI < 0.55 on 1st post-transplant day	1.313	[0.820; 2.101]	0.257
Interval between venous and arterial reperfusion (min)	1.002	[0.998; 1.006]	0.401

Table 7 Cause of death according to RI group

Cause of Death	IR < 0.55	IR ≥ 0.55	<i>p</i>
Primary nonfunction	4 (11.8%)	5 (4.9%)	0.433
HAT	2 (5.9%)	1 (1%)	0.381
Biliary complications	3 (8.8%)	8 (7.8%)	0.99
Rejection	2 (5.9%)	7 (6.9%)	0.99
Disease recurrence (HCC, HCV, HBV, etc.)	3 (8.8%)	17 (16.7%)	0.254
Opportunistic infection	1 (2.9%)	1 (1.4%)	0.99
Hemorrhagic Shock	3 (8.8%)	2 (1.9%)	0.253
Sepsis	5 (14.7%)	10 (9.8%)	0.830
Other	5 (14.7%)	22 (21.6%)	0.318
Unknown	6 (17.6%)	29 (28.4%)	

thrombosis. This finding contrasts with previous studies, which report an incidence of graft loss approaching 50% [15]. This discrepancy may indicate that the choice for early surgical revascularization, which include arterial thrombectomy with intra-arterial alteplase, redo of arterial anastomosis and creation of an arterial conduit, is successful in preventing early graft loss. However, these patients had an increased incidence of biliary complications, including fistula, abscess and stenosis. This finding is in consonance with previous literature studies [16, 17]. Additionally, HAT was associated with decreased graft survival.

Regarding the RI, our study showed an association between RI < 0.55 on the first post-transplant day both to HAT and worse graft survival. On the other hand, no association between RI < 0.55 on 3rd and 5th post-transplant day and graft survival was found. To the best of our knowledge, this is the first study showing an association between low hepatic artery RI and decreased graft survival. Although routinely estimated on DUS examinations, very few studies have investigated the role of the RI as a predictor of outcome and prognostic factor in patients undergoing either adult or pediatric liver transplantation. Indeed, a RI < 0.55

likely may be related to intimal flap or kinking of the arterial stenosis. Gaspari et al. [10] found no association between RI and vascular complications and 90-day mortality. In contrast to our findings, in a study by Lv et al. [18], high RI (>0.68) on post-operative day 3 was associated with increased risk of early allograft dysfunction, but no association on post-operative day 1 was identified. However, that study included only living-donor liver grafts, which differ from deceased donor grafts in terms of incidence of postoperative complications and causes of graft dysfunction [19, 20].

The reason for inferior graft survival in patients with low RI is unclear. Low RI has been associated with insufficient arterial flow, which may occur in the context of steal syndrome, celiac trunk stenosis and hemodynamic instability [12]. A recent study has shown that low arterial flow has a negative impact on transplant outcomes [21]. Patients with hepatic arterial flow <400 ml/min had increased incidence of biliary complications and inferior graft survival as compared to patients with normal flow (>400 ml/min). In our study, although vascular flow was not available for our analysis, low RI in the early postoperative period had a negative impact on graft survival, which might represent a surrogate marker of poor arterial flow.

On univariate analysis, four other variables showed a correlation with graft survival: intraoperative bleeding (L), RBC transfusion, MELD score, interval between venous and arterial reperfusion. However, on multivariate analysis, $RI < 0.55$ on the first post-transplant day was the only variable associated with decreased graft survival, reinforcing the value of RI on DUS as an independent prognostic tool. Interestingly, there was an increased incidence of graft loss due to primary nonfunction in patients with $RI < 0.55$ (16% vs. 7%). However, given the small sample size, no statistically significant difference was detected between the two groups. Recently, a multicenter cohort study has developed a score (EASE Score) to predict the risk of graft failure over the first 90 post-LT days [22]. Such score included both parenchymal and vascular factors, which provided a clear indication to list for retransplant. Unfortunately, this study was published only recently (in 2020). Thus, the score was not utilized in the criteria to list the patients for retransplantation in our study.

As the biliary tree is primarily supplied by the liver arterial inflow [23], it could be expected that abnormalities in arterial blood flow could lead to increased risk of biliary complications. Liao et al. [24] performed a case-control study in pediatric living donor transplant recipients and found lower RI in patients with biliary complications as compared to the control group (0.58 vs. 0.72). Conversely, in our study, the incidence of biliary complications was comparable between the RI groups on post-transplant day 1 (19.6% $RI < 0.55$ vs. 12.7% $RI \geq 0.55$, $p = 0.135$). In contrast, patients with HAT had increased incidence of biliary complications (43.5% vs. 12.1%).

A $RI < 0.55$ was not statistically associated to any cause of graft failure. However, patients with RI had times more graft losses due to HAT and PNF was twice more common. The lack of statistical significance probably was due to the small sample size (a type II error).

Our study has some limitations. The retrospective design may limit the interpretation of the results. However, data was extracted from a database that has been filled prospectively. This fact strengthens the significance of our findings. Additionally, although the extended eighteen-year cohort may demonstrate different historical periods of the service, the majority of the team of surgeons has remained the same.

Conclusion

The use of DUS on LT recipients in the early post-transplant period offers the possibility of early diagnosis of vascular complications, enabling the transplant team to perform timely therapeutic interventions, which might be successful in averting graft loss. Also, an intensive DUS protocol used in this study (1st, 3rd and 5th post-LT days) was helpful in diagnosing HAT occurring between 1st and 7th post-LT days. Additionally, according to our data, low RI (<0.55) on the first postoperative day also provides prognostic information regarding graft survival. Thus, this study reinforces the usefulness of DUS as an important tool in the early post-transplant period.

Author's contributions R.P.C.—Study conception and design, acquisition of data, analysis and interpretation of data, drafting of manuscript. G.L.S.—Analysis and interpretation of data, drafting of manuscript. T.J.M.G.F.—Study conception and design, critical revision of manuscript. G.S.V.—Acquisition of data, critical revision of manuscript. J.E.P.—Acquisition of data, critical revision of manuscript. B.R.—Acquisition of data, critical revision of manuscript. R.K.S.—Acquisition of data, critical revision of manuscript. L.P.—Acquisition of data, critical revision of manuscript. A.A.—Study conception and design, critical revision of manuscript. M.R.A.S.—Study conception and design, critical revision of manuscript. F.H.F.—Study conception and design, critical revision of manuscript. M.F.C.—Study conception and design, acquisition of data, analysis and interpretation of data, critical revision of manuscript. C.R.P.K.—Study conception and design, analysis and interpretation of data, drafting of manuscript.

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Declarations

Ethical approval This study complies with ethical standards and was approved by the Hospital de Clínicas de Porto Alegre Institutional Review Board (*Grupo de Pesquisa e Pós-Graduação—GPPG HCPA*). (2019-0564).

Research involving human participants All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was waived by the ethics committee because this is an observational retrospective study.

Competing interests The authors have no conflicts of interest to disclose.

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