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# **Liver transplantation normalizes serum hepcidin level and cures iron metabolism ALTERATIONS in HFE hemochromatosis**

Short Title: Hemochromatosis liver transplantation

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**Abbreviations**

LT: Liver Transplantation

HCC: Hepatocellular Carcinoma

HCV: Hepatitis C virus

MRI: Magnetic Resonance Imaging

HH: *HFE* related Hemochromatosis

LIC: Liver iron concentration

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## ABSTRACT

**Background:** Defects in human hemochromatosis protein (HFE) cause iron overload due to reduced hepatic hepcidin secretion. Liver transplantation (LT) is a key treatment for potential complications from HFE-related hereditary hemochromatosis (HH). This study evaluated hepcidin secretion and iron burden after LT to elucidate HH pathophysiology. **Methods:** Patients (n=18) homozygous for the p.Cys282Tyr mutation in the *HFE* gene underwent LT between 1999 and 2008. Serum iron, serum hepcidin, and hepatic iron concentrations were determined before LT and at the end of follow-up (median 57 months). Mortality and causes of death were determined. Survival was compared to that of the overall patient population that received LT. **Results:** Before LT, serum hepcidin levels were low ( $0.54 \pm 2.5$  nmol/L; normal range: 4-30 nmol/L). After LT, 11 patients had iron evaluations; none received iron depletion therapy; all had normal transferrin saturation. The mean serum ferritin was  $185 (\pm 99)$   $\mu$ g/L. Magnetic resonance imaging showed that iron overload was absent in 9 patients, mild in one patient with metabolic syndrome, and high ( $180 \mu$ mol/g) in one patient with hereditary spherocytosis unmasked after liver transplantation. At the end of follow-up, serum hepcidin was normal in 10 patients ( $11.12 \pm 7.6$  nmol/L;  $p < 0.05$ ) and low in one patient with iron deficiency anemia. Survival was 83% and 67% at one and 5 years, respectively. Survival was similar for patients with HH and patients that received LT for other causes. **Conclusion:** This study demonstrated that, in HH, LT normalized hepcidin secretion and prevented recurrence of hepatic iron overload. Survival was similar to that of patients that received LTs for other liver diseases.

## INTRODUCTION

Since 1865, when Trousseau first described hemochromatosis and demonstrated its genetic nature (1), many studies have shed light on its putative pathophysiological mechanism. The most important breakthrough was the discovery of the gene that encoded human hemochromatosis protein (*HFE*). This made it possible to diagnose the most common form of hereditary hemochromatosis (HH)(2), the *p.Cys282Tyr* mutation (C282Y) in the *HFE* gene. In addition, these discoveries enabled discrimination of *HFE*-related HH from various secondary causes of iron overload and other rare genetic entities(3). The underlying mechanism of HH was initially thought to be related to the role of *HFE* in regulating iron absorption at the intestinal crypt (4), which was supported by the observation that excessive iron absorption occurred in HH(5). However, this hypothesis has not been confirmed thereafter.

Another major breakthrough in understanding iron metabolism in HH was the discovery of hepcidin and its role in iron metabolism(6, 7). Mainly secreted by the liver, this small peptide was shown to interact with ferroportin, the only known cellular iron exporter, and this interaction induced ferroportin internalization and degradation(8). Through its regulation of ferroportin, hepcidin can reduce iron export from macrophages and enterocytes into the bloodstream. Consequently, the liver represents the major regulator of iron metabolism. In patients with HH, serum hepcidin levels were shown to be inappropriately low (9).

The molecular impact of the *HFE* C282Y mutation has not been fully elucidated. It is thought to inhibit the ability of *HFE* to interact with  $\beta 2$  microglobulin and transferrin receptor 1 (TFR1)(10). The interactions between *HFE* and TFR1 and TFR2 (11, 12) play important roles in iron sensing at the hepatocyte membrane, which regulates hepcidin expression. Mice with *Hfe* gene knock-outs display a hemochromatosis phenotype with inappropriately low hepcidin expression (13, 14). Mice with a liver-specific *Hfe* knock-out presented the same phenotype(15). Conversely, hepatic-specific expression of wild-type *HFE* in *HFE* knock-out mice increased hepcidin expression and lowered liver iron levels(16). This finding suggests that the liver is the central regulatory site for iron metabolism regulation. In a recent study, Garuti *et al.* reported that, when a liver with wild-type *HFE* was transplanted into a *Hfe* knock-out mouse, the hemochromatosis iron loading phenotype was reversed and hepcidin expression was normalized at the transcriptional level(17). From a clinical viewpoint,

human case studies have not provided clear results. In some studies, a normal liver was transplanted into a patient with HH, and in other studies, a HH liver was transplanted into normal patients (18-22). The results did not show the expected evolution of iron burden due to these liver transplantations. Moreover, very few cases of HH have been reported, and among those, assessments of the iron burden were often incomplete, and the evolution of hepcidin levels was not documented.

In the setting of liver transplantation, poor survival rates have been generally associated with iron overload, particularly in patients with HH, compared to patients with liver diseases of alcoholic or viral origin. It was suggested that hemochromatosis increased the propensity for infections and associated cardiovascular diseases(23-27). However, those studies were limited by various biases; for example, earlier studies were performed before the availability of *HFE* (23, 24) testing, and thus, associations with hemochromatosis were likely to reflect various conditions that caused iron overload. More recent studies have identified patients with confirmed *HFE* mutations, with a family history of HH, or with a HLA A3B7 haplotype; in those studies, either the diagnosis was retrospective and included historical cases with a highly severe phenotype(26, 27), or the control populations were not representative of other liver diseases (27). Consequently, it remains a matter of debate whether survival after liver transplantation is affected by *HFE* C282Y homozygosity and iron overload.

Therefore, the present study aimed (a) to evaluate the role of the liver in regulating iron metabolism, based on the long-term evolution of iron metabolism after liver transplantation in patients homozygous for *HFE* C282Y; and (b) to analyze survival after transplantation in patients homozygous for *HFE* C282Y compared to patients that received transplants for other liver diseases, but underwent similar surgical procedures and medical management over the same time period.

## PATIENTS AND METHODS

### PATIENTS

All patients that underwent a first, single organ, liver transplantation in our center from 01/01/1999 to 12/31/2008 were eligible for our study. We collected data regarding underlying liver disease, indications for liver transplantation, and pre-transplantation liver function evaluations (Child-Pugh Score) from the national transplant registry database (Agence de la Biomédecine). The records of patients with hemochromatosis were reviewed. A local database of patients with *HFE*-related hemochromatosis was compared with the records of patients that underwent liver transplantations to identify patients that may have been omitted. Patients were included in the *HFE* hemochromatosis group only when *HFE* C282Y homozygosity was confirmed by genetic testing. In 2009, patients with *HFE* hemochromatosis were asked to participate in this study to reassess their iron metabolism, and they provided informed, written consent. This study was in accordance with the declaration of Helsinki. According to national policy no donor organs were obtained from executed prisoners or other institutionalized persons.

### FOLLOW UP DATA

Patients were followed as outpatients at least once per year. The date and cause of death data were acquired prospectively from patient records or by directly contacting the general practitioners within the framework of the national transplant registry. Serum samples obtained before liver transplantation that were available in the serum bank were acquired for performing biochemical tests. The vital status of each patient was determined from the status recorded at the last follow-up visit to our center. Iron-related treatment data were retrospectively collected from the records, and reviewed with the patient at the time of the inclusion visit. Patients lost to follow-up or to graft loss were considered deceased. The end of follow-up was fixed as the 30<sup>th</sup> of June 2012.

## IRON METABOLISM

Biochemical tests were performed on serum samples to assess iron metabolism (serum iron, serum transferrin, transferrin saturation, serum ferritin) and to measure C reactive protein. Serum samples were obtained before liver transplantation and during the follow-up. Samples before liver transplantation were obtained from serum bank gathered in fasting patients during the evaluation before liver transplantation and stored at -80°C. Serum hepcidin levels were determined with an enzyme immunoassay (Peninsula Laboratories, Bachem, San Carlos USA) which was evaluated in a Round Robin 2 for Hepcidin assay and was shown to have satisfactory reliability (28). Serum hepcidin/ferritin ratios were calculated as follows: (serum hepcidin/serum ferritin) X100.

At the inclusion visit, the liver iron concentration (LIC) was determined with magnetic resonance imaging (MRI).(29) Spleen iron concentration was semi-quantitatively estimated with MRI and the same method used for the liver.

## STATISTICAL METHODS

Results are reported as the median value  $\pm$  standard deviation. Quantitative variables were compared with the Wilcoxon signed rank test. Cumulative survival estimates and survival curves of patients with liver transplants were determined with the Kaplan Meyer method. Survival curves were compared between groups with the Log Rank test. Statistics were performed with SPSS 17.0. All tests were two-tailed, and the statistical significance level was set at  $p < 0.05$ .



## RESULTS

### PATIENT CHARACTERISTICS

From 1999 to 2008, 736 patients underwent a first liver transplantation, 340 had alcoholic liver disease (65 with hepatocellular carcinoma [HCC]), 96 had viral hepatitis C (21 with HCC), 34 had acute liver failure, 20 had viral hepatitis B, 53 had congenital or auto-immune biliary diseases, 61 had other liver diseases (auto-immune hepatitis, vascular disease, enzymatic deficiencies, rare tumors), 114 had HCC without definite information for the underlying disease, and 18 had *HFE*-related hemochromatosis. The characteristics of the patients that received liver transplants to treat *C282Y HFE*-related hemochromatosis are presented in Table 1. The mean age at diagnosis of hemochromatosis was 48.7 ( $\pm 7$ ) years and the mean age at liver transplantation was 56 ( $\pm 7$ ) years; the mean follow-up time after liver transplantation was 68  $\pm 45$  months. The main indication for liver transplantation was HCC without liver failure.

### EVOLUTION OF IRON BURDEN AND SERUM HEPcidIN LEVELS

We evaluated iron metabolism in 16 of the 18 patients with available biological samples collected before liver transplantation (at the time of liver transplantation evaluation). Eleven patients were fully iron depleted before liver transplantation, whereas five patients received the liver transplantation before total iron depletion was fully obtained with phlebotomy treatment. These patients received a diagnosis of hemochromatosis concomitant with the liver transplantation indication diagnosis. One patient did not undergo any phlebotomy before liver transplantation. Biochemical evaluations of iron metabolism after liver transplantation were available for 15 of the 18 patients at different time points during follow-up (Table 2). Only one patient required occasional bloodletting (less than 3 times a year) after liver transplantation.

The median follow-up time for the iron burden evaluation was 60 $\pm$ 35 months. The median serum transferrin saturation was 68 $\pm$ 30% before, and 28 $\pm$ 8.5% after liver transplantation ( $p=0.021$ ). Before liver transplantation, the median serum hepcidin level (N=4-30) and hepcidin/ferritin ratio (N=4-30) were 1.61 $\pm$ 3.6 nmol/L and 0.35 $\pm$ 3.6, respectively. After liver transplantation, hepcidin levels significantly increased (13.2 $\pm$ 8.1 nmol/L,

$p=0.006$ ) and hepcidin/ferritin ratios significantly increased ( $6.93 \pm 8.75$ ,  $p=0.015$ ). All except one patient achieved normal hepcidin values. This patient had pulmonary fibrosis, which required continuous oxygen therapy. The patient eventually died of respiratory failure. His serum ferritin and transferrin saturation levels were normal.

The LIC, determined by MRI, was available for 11 patients (Table 2). Two patients had hepatic iron overload; of these, one patient (n° 9) had slightly elevated serum ferritin with normal transferrin saturation and mild LIC elevation. This patient was followed for recurrence of excessive alcohol consumption and had features of metabolic syndrome (diabetes, body mass index=31, waist circumference= 104 cm, and high serum triglyceride levels). The other patient (n°8) had high serum ferritin and LIC values and was followed for hereditary spherocytosis that was unmasked only after liver transplantation (hemoglobin level: 7-10 g/dl). This patient's post-liver transplantation history included transfusions, iron supplementation, and erythropoietin treatment, while she had no history of hematological condition during the 20 years of phlebotomy treatment for hemochromatosis before liver transplantation.

## SURVIVAL AND CAUSES OF DEATH

Overall patient survival was 89% at one year, 70% at 5 years, and 55% at 10 years. Survival of patients with HH was 83% at one year and 67% at five years. The follow-up durations and causes of death for patients with HH are detailed in Table 1. Patients mainly died of sepsis or cancer; only one fatal vascular event occurred. Kaplan-Meier survival curves are shown in Figure 1. There were no statistical differences (Log Rank test:  $p=0.40$ ) between survival of patients with HH and the control population (Figure 1A).

Among our entire population, we separated out all patients ( $n=135$ ) that received liver transplantations for HCC without liver failure (Child-Pugh score  $\leq 6$ ), regardless of the underlying disease, and compared these to patients with HH. The survival curves are shown in Figure 1B. The log rank test did not detect any statistical difference between survival of patients with HCC and those with HH ( $p=0.56$ ).

Finally, we compared survival according to the underlying disease, regardless of the indication for liver transplantation. The patients were allocated to groups with alcoholic liver disease, hepatitis C, and acute liver

failure. We compared survival of these groups to that of the HH group (Figure 1C). The log rank test indicated that patients with hepatitis C had significantly lower survival rates than those with alcoholic liver diseases ( $p=0.001$ ) and those with acute liver failure ( $p=0.024$ ). All other comparisons showed no statistically significant differences.

## DISCUSSION

This study was the first to report long-term follow-up data on serum hepcidin and iron metabolism profiles after liver transplantation in a well-defined group of patients homozygous for *HFE* C282Y. In addition, it is the first to definitely demonstrate the paramount role of liver in human HH. Our results showed, as expected, that patients with HH had low serum hepcidin levels, and that serum hepcidin levels were normalized after liver transplantation. Moreover, we found that, after a median follow-up of 5 years without iron depletion treatment, in patients without confounding factors, normal serum hepcidin levels were associated with normal biological iron metabolism and normal liver iron content, based on MRI. The patient and graft survival rates after liver transplantation were not significantly different between patients with HH and the overall population of patients that received liver transplantations.

These results shed light on the evolution of iron burden in patients with HH. Although our cohort of patients was relatively small, we used rigorous selection criteria that excluded other causes of iron overload. Moreover, the iron burden assessment was based on biochemical and imaging data that were available over a long follow-up period.

Several case report studies (18-22, 30, 31) have previously attempted to elucidate the role of the liver in HH. However, the results showed discrepancies, and they precluded definite conclusions, due to the small numbers of patients, the lack of genetic testing, the short-term follow-ups, and the lack of hepcidin assessments. Kowdley *et al.* (27) studied LIC after liver transplantation of patient with HH. Their results indicated that iron overload did not recur in patients with HH, based on measurements of serum transferrin saturation and serum ferritin levels. However, they lacked LIC assessments for half of the surviving patients. Moreover, that study was performed before the discovery of hepcidin's role in iron metabolism (7); thus, no data was available on hepcidin secretion.

In the present study, after liver transplantation, we found no increases in serum transferrin saturation, considered the earliest biochemical event in HH. In addition, we found no hepatic iron overload in the entire study group. Importantly, in our series, only one patient received occasional phlebotomy treatment after transplantation, which could have hampered the recurrence of iron overload. We found two patients with

modified iron parameters, but they both exhibited comorbidities that influenced iron metabolism. This finding underlined the importance of a careful search for potential confounding cofactors.

One of the major difficulties in describing the outcome of HH after liver transplantation has been the lack of definite markers for HH and its variable expression (32). However, we were able to measure serum hepcidin, which exerts a primary regulatory role in iron metabolism and in hemochromatosis expression (33, 34). This provided a more precise, relevant evaluation of liver transplantation outcome. In mice, Garuti *et al.* (17), found that transplantation of *HFE* wild type livers in *HFE* knock-out mice resulted in normal hepatic hepcidin expression at the mRNA level and a trend toward decreased iron burden. Moreover, transplantation of *HFE* knock-out livers in *HFE* wild type mice resulted in low hepatic hepcidin expression and the occurrence of iron overload. Here, we used this hepcidin approach for evaluating human liver transplantations. We established for the first time that serum hepcidin levels, which were abnormally low before liver transplantation, were fully normalized after liver transplantation.

Our finding that serum hepcidin levels were low before liver transplantation was consistent with previous studies in patients with HH. Moreover, we confirmed that the hepcidin/ ferritin ratio was preferable to the serum hepcidin evaluation. Among five patients (n°3,4,10,15 and 18) with normal hepcidin values before liver transplantation, three (n°3,4 and 15) had very high ferritin values; thus, the hepcidin/ferritin ratio was low, due to inadequate hepcidin synthesis, and this confirmed the hepcidin-deficient phenotype. Two patients had normal hepcidin levels and hepcidin/ferritin ratios (n°10, 18); both were diagnosed with HCC. We speculate that inflammation, related either to the cancer disease, or to the effect of cancer treatment applied during the time the patient spent on the waiting list, or abnormal hepcidin secretion by the tumor, contributed to the normal hepcidin levels for these patients. Of note, two patients (n°1 and 5) had normal ratios, with very low hepcidin and serum ferritin levels. This could indicate that the hepcidin/ferritin ratio may be inadequate in cases with low serum ferritin levels. The same explanation may apply to patients 1 and 18 who, after transplantation, presented with abnormally low hepcidin / ferritin ratio. Cirrhosis itself has been associated with reduced hepatic expression, however most of our patients were free of liver failure therefore it is unlikely to have modified our serum hepcidin value. Since hepcidin levels have been shown to decrease during the induction phase of phlebotomy treatment (9), we cannot exclude that this factor contributed to the pre-transplantation decreased hepcidin values. However, the data obtained with the hepcidin/ferritin ratios

indicated that hepcidin remained relatively low when compared to the degree of iron stores, accordingly to the observations previously reported in patients exhibiting HFE hemochromatosis, and at a similar level to that of the untreated patients.

After liver transplantation, serum hepcidin was normalized, and iron parameters remained normal for 5 years. This confirmed that the liver was the main producer of hepcidin in humans, and that normalization of hepcidin levels in the serum was associated with reversion of abnormal iron metabolism. Two patients with very high ferritin levels before transplant normalized their ferritin values after transplantation. It is possible that taking out most of the iron burden by removing the diseased liver, and restoring normal iron regulation with the new liver, may have led to this evolution. Altogether, these data supported the view that hepcidin is a major actor in systemic iron regulation, and it agreed with previous data obtained in mice (17, 34) [ENREF 33](#).

It is likely that hepatic transplantation might also cure other genetic forms of hemochromatosis, unrelated to HH; for example, iron overload due to mutations in *HJV*, *HAMP*, or *TFR2* genes. Indeed, like *HFE*, both *HJV* and *TFR2* genes are involved in the transduction of signals related to iron sensing. Furthermore, like *HFE*, these two genes are expressed at the level of the hepatocyte membrane. This observation takes on particular importance when we consider that these three mutated genes may be responsible for severe forms of juvenile hemochromatosis. Although the *HFE* gene is expressed in a large number of tissues (2), our clinical data support the view that *HFE* expression in non-liver cells is unlikely to play a major role in iron metabolism during genetic hemochromatosis.

This study also addressed the important, debated issue of patient and graft survival after liver transplantation in patients with HH. Our results showed that survival rates were not significantly different in patients with HH and the overall population of patients that received liver transplants. However, this result contrasted with previous reports (23-27). Indeed, liver transplantation in patients with HH has been associated with lower survival, due to more frequent infections and cardiovascular diseases (27). However, some of those studies were conducted before definitive criteria were available for HH diagnosis. For example, Kowdley *et al.* (27) diagnosed HH in patients prior to liver transplantation, but only 43% of patients underwent a genetic test confirmation. It is known that iron overload can occur in various liver diseases, and it can increase with the severity of the disease (35-37). In a study by Brandhagen *et al.*, (38) only 10% of transplanted patients with iron

overload were homozygous for *HFE* C282Y. Moreover, most previous studies lacked an evaluation of liver disease severity with the Child-Pugh score. Thus, the lack of a definitive diagnosis, combined with the possible selection of severe patients at inclusion could have induced a selection bias, which influenced the findings that HH was associated with increased complications and mortality.

The present study included patients that were prospectively diagnosed and genetically confirmed for HH. These patients showed survival rates similar to those of the overall population. When we assessed survival according to the underlying liver disease, we did not find differences between patients with HH and those with other liver diseases. Most of our patients were iron depleted before liver transplantation; only six had presented biological signs of iron overload at the time of liver transplantation. Thus, we did not have sufficient statistical power to assess survival between iron depleted and non-iron depleted patients. However, it is likely that the previously described low survival rates of patients with HH were related to iron overload, regardless of the underlying disease, rather than specifically related to the genetic defect. This hypothesis is consistent with the recent study by Yu *et al.* (39) which showed that post-liver transplantation survival in patients with hemochromatosis was higher in studies conducted more recently compared to survival reported in older studies. However, as acknowledged by the authors, that study lacked definitive genetic diagnoses of patients with HH and did not consider the potential association between HCC and hemochromatosis.

It is noteworthy that, in our population, HCC was the main indication for liver transplantation. In addition, only one patient had liver failure associated with excessive alcohol intake. This observation was fully consistent with the natural history of liver cirrhosis in HH, where liver failure is rarely seen in the absence of hepato-toxic cofactors (the case in nearly all our patients). Therefore, this confirmed that the major liver complication in HH was HCC, consistent with our experience and also with a study by Fracanzani *et al.* (40) A study by Crawford *et al.* (26) showed that, in patients with genetic hemochromatosis that received liver transplants, mortality was mainly related to HCC recurrence. However, some patients exhibited a tumor that was not within the Milan criteria, because the study was performed before the establishment of HCC guidelines. In contrast, we found that our patients with HH (mainly diagnosed with HCC classified as Child-Pugh A cirrhosis) had survival rates similar to our control population of patients that received liver transplants for treating HCC (also diagnosed with Child-Pugh A cirrhosis). Thus, among patients with and without HH, defined with the same currently

accepted criteria, the patients with HH did not exhibit increased risk of HCC recurrence after liver transplantation.

In conclusion, our study in humans demonstrated that liver transplantation cured the iron overload phenotype and the biological defects in HH by normalizing hepcidin synthesis. These data further supported the notion that the liver plays a primary role in iron metabolism. Moreover, our results showed that survival of patients with HH after liver transplantation was similar to that of the overall population of patients that received liver transplants.



## REFERENCES

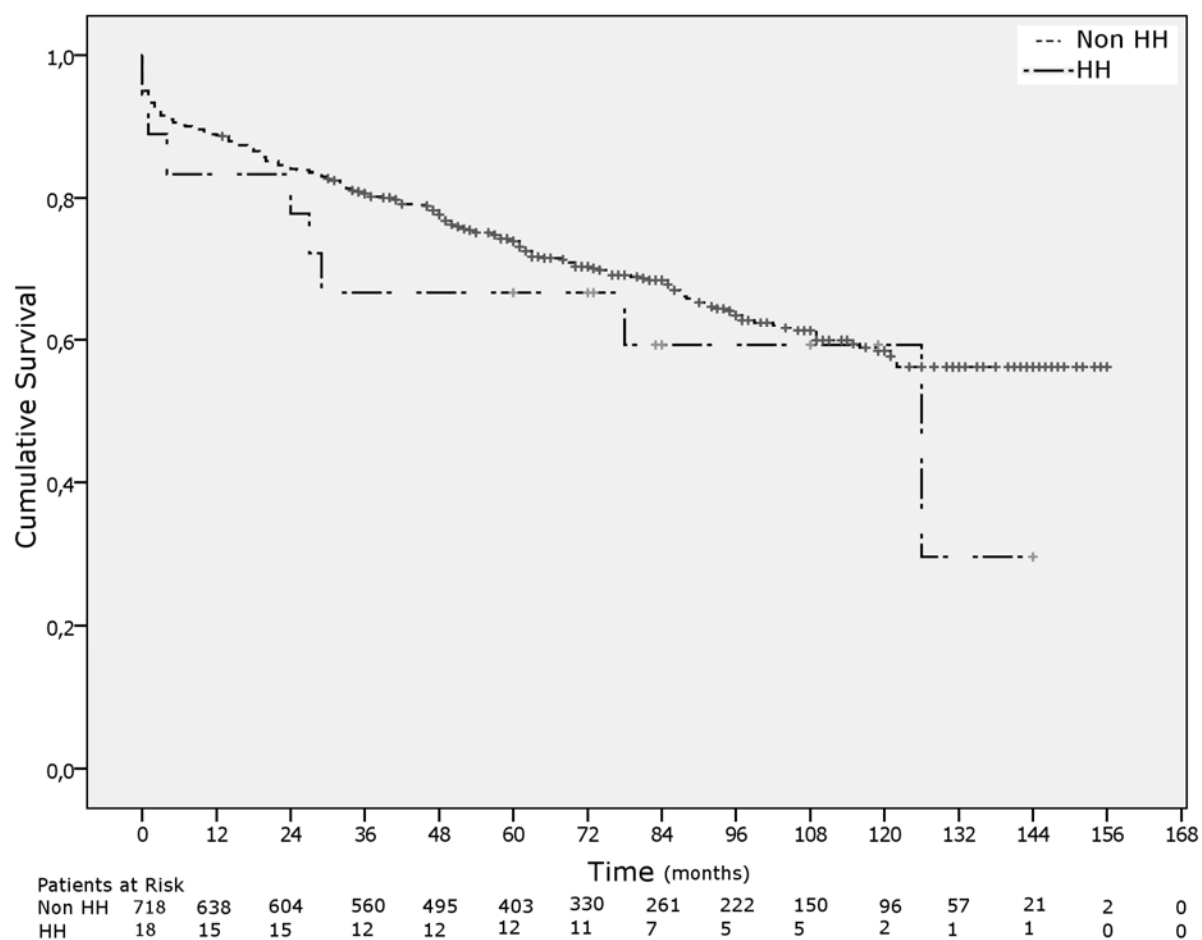
1. Simon M, Bourel M, Genetet B, Fauchet R. Idiopathic hemochromatosis. Demonstration of recessive transmission and early detection by family HLA typing. *N Engl J Med* 1977;297:1017-1021.
2. Feder JN, Gnirke A, Thomas W, Tsuchihashi Z, Ruddy DA, Basava A, Dormishian F, et al. A novel MHC class I-like gene is mutated in patients with hereditary haemochromatosis. *Nat Genet* 1996;13:399-408.
3. Brissot P, Bardou-Jacquet E, Jouanolle AM, Loreal O. Iron disorders of genetic origin: a changing world. *Trends Mol Med* 2011;17:707-713.
4. Parkkila S, Waheed A, Britton RS, Feder JN, Tsuchihashi Z, Schatzman RC, Bacon BR, et al. Immunohistochemistry of HLA-H, the protein defective in patients with hereditary hemochromatosis, reveals unique pattern of expression in gastrointestinal tract. *Proc Natl Acad Sci U S A* 1997;94:2534-2539.
5. Parkkila S, Niemela O, Britton RS, Fleming RE, Waheed A, Bacon BR, Sly WS. Molecular aspects of iron absorption and HFE expression. *Gastroenterology* 2001;121:1489-1496.
6. Park CH, Valore EV, Waring AJ, Ganz T. Hepcidin, a urinary antimicrobial peptide synthesized in the liver. *J Biol Chem* 2001;276:7806-7810.
7. Pigeon C, Ilyin G, Courselaud B, Leroyer P, Turlin B, Brissot P, Loreal O. A new mouse liver-specific gene, encoding a protein homologous to human antimicrobial peptide hepcidin, is overexpressed during iron overload. *J Biol Chem* 2001;276:7811-7819.
8. Nemeth E, Tuttle MS, Powelson J, Vaughn MB, Donovan A, Ward DM, Ganz T, et al. Hepcidin regulates cellular iron efflux by binding to ferroportin and inducing its internalization. *Science* 2004;306:2090-2093.
9. van Dijk BA, Laarakkers CM, Klaver SM, Jacobs EM, van Tits LJ, Janssen MC, Swinkels DW. Serum hepcidin levels are innately low in HFE-related haemochromatosis but differ between C282Y-homozygotes with elevated and normal ferritin levels. *Br J Haematol* 2008;142:979-985.
10. Feder JN, Penny DM, Irrinki A, Lee VK, Lebron JA, Watson N, Tsuchihashi Z, et al. The hemochromatosis gene product complexes with the transferrin receptor and lowers its affinity for ligand binding. *Proc Natl Acad Sci U S A* 1998;95:1472-1477.
11. D'Alessio F, Hentze MW, Muckenthaler MU. The hemochromatosis proteins HFE, Tfr2, and HJV form a membrane-associated protein complex for hepcidin regulation. *J Hepatol* 2012.
12. Goswami T, Andrews NC. Hereditary hemochromatosis protein, HFE, interaction with transferrin receptor 2 suggests a molecular mechanism for mammalian iron sensing. *J Biol Chem* 2006;281:28494-28498.
13. Zhou XY, Tomatsu S, Fleming RE, Parkkila S, Waheed A, Jiang J, Fei Y, et al. HFE gene knockout produces mouse model of hereditary hemochromatosis. *Proc Natl Acad Sci U S A* 1998;95:2492-2497.
14. Ahmad KA, Ahmann JR, Migas MC, Waheed A, Britton RS, Bacon BR, Sly WS, et al. Decreased liver hepcidin expression in the Hfe knockout mouse. *Blood Cells Mol Dis* 2002;29:361-366.
15. Vujic Spasic M, Kiss J, Herrmann T, Galy B, Martinache S, Stolte J, Grone HJ, et al. Hfe acts in hepatocytes to prevent hemochromatosis. *Cell Metab* 2008;7:173-178.
16. Gao J, Chen J, De Domenico I, Koeller DM, Harding CO, Fleming RE, Koeberl DD, et al. Hepatocyte-targeted HFE and TFR2 control hepcidin expression in mice. *Blood* 2010;115:3374-3381.

17. Garuti C, Tian Y, Montosi G, Sabelli M, Corradini E, Graf R, Ventura P, et al. Hepcidin expression does not rescue the iron-poor phenotype of Kupffer cells in Hfe-null mice after liver transplantation. *Gastroenterology* 2010;139:315-322 e311.
18. Adams PC, McAlister V, Chakrabarti S, Levstik M, Marotta P. Is serum hepcidin causative in hemochromatosis? Novel analysis from a liver transplant with hemochromatosis. *Can J Gastroenterol* 2008;22:851-853.
19. Dwyer JP, Sarwar S, Egan B, Nolan N, Hegarty J. Hepatic iron overload following liver transplantation of a C282Y homozygous allograft: a case report and literature review. *Liver Int* 2011;31:1589-1592.
20. Ismail MK, Martinez-Hernandez A, Schichman S, Chaudhry S, Waters B. Transplantation of a liver with the C282Y mutation into a recipient heterozygous for H63D results in iron overload. *Am J Med Sci* 2009;337:138-142.
21. Adams PC, Jeffrey G, Alanen K, Chakrabarti S, Preshaw R, Howson W, Grant D. Transplantation of haemochromatosis liver and intestine into a normal recipient. *Gut* 1999;45:783.
22. Adams PC, Ghent CN, Grant DR, Frei JV, Wall WJ. Transplantation of a donor liver with haemochromatosis: evidence against an inherited intrahepatic defect. *Gut* 1991;32:1082-1083.
23. Kilpe VE, Krakauer H, Wren RE. An analysis of liver transplant experience from 37 transplant centers as reported to Medicare. *Transplantation* 1993;56:554-561.
24. Kowdley KV, Hassanein T, Kaur S, Farrell FJ, Van Thiel DH, Keeffe EB, Sorrell MF, et al. Primary liver cancer and survival in patients undergoing liver transplantation for hemochromatosis. *Liver Transpl Surg* 1995;1:237-241.
25. Tung BY, Farrell FJ, McCashland TM, Gish RG, Bacon BR, Keeffe EB, Kowdley KV. Long-term follow-up after liver transplantation in patients with hepatic iron overload. *Liver Transpl Surg* 1999;5:369-374.
26. Crawford DH, Fletcher LM, Hubscher SG, Stuart KA, Gane E, Angus PW, Jeffrey GP, et al. Patient and graft survival after liver transplantation for hereditary hemochromatosis: Implications for pathogenesis. *Hepatology* 2004;39:1655-1662.
27. Kowdley KV, Brandhagen DJ, Gish RG, Bass NM, Weinstein J, Schilsky ML, Fontana RJ, et al. Survival after liver transplantation in patients with hepatic iron overload: the national hemochromatosis transplant registry. *Gastroenterology* 2005;129:494-503.
28. Kroot JJ, van Herwaarden AE, Tjalsma H, Jansen RT, Hendriks JC, Swinkels DW. Second round robin for plasma hepcidin methods: first steps toward harmonization. *Am J Hematol*;87:977-983.
29. Gandon Y, Olivie D, Guyader D, Aube C, Oberti F, Sebille V, Deugnier Y. Non-invasive assessment of hepatic iron stores by MRI. *Lancet* 2004;363:357-362.
30. Dabkowski PL, Angus PW, Smallwood RA, Ireton J, Jones RM. Site of principal metabolic defect in idiopathic haemochromatosis: insights from transplantation of an affected organ. *BMJ* 1993;306:1726.
31. Koskinas J, Portmann B, Lombard M, Smith T, Williams R. Persistent iron overload 4 years after inadvertent transplantation of a haemochromatotic liver in a patient with primary biliary cirrhosis. *J Hepatol* 1992;16:351-354.
32. Allen KJ, Gurrin LC, Constantine CC, Osborne NJ, Delatycki MB, Nicoll AJ, McLaren CE, et al. Iron-overload-related disease in HFE hereditary hemochromatosis. *N Engl J Med* 2008;358:221-230.
33. Muckenthaler M, Roy CN, Custodio AO, Minana B, deGraaf J, Montross LK, Andrews NC, et al. Regulatory defects in liver and intestine implicate abnormal hepcidin and Cybrd1 expression in mouse hemochromatosis. *Nat Genet* 2003;34:102-107.

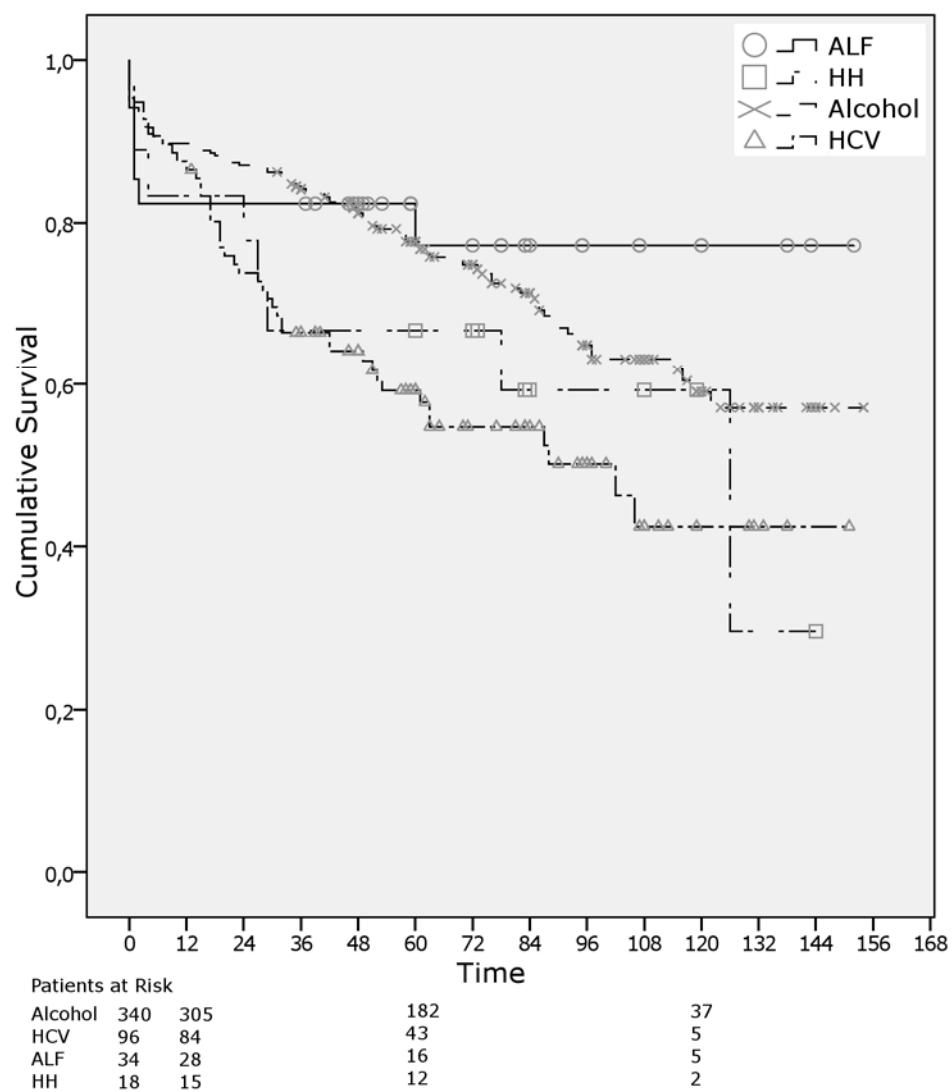
34. Nicolas G, Viatte L, Lou DQ, Bennoun M, Beaumont C, Kahn A, Andrews NC, et al. Constitutive hepcidin expression prevents iron overload in a mouse model of hemochromatosis. *Nat Genet* 2003;34:97-101.
35. O'Glasser AY, Scott DL, Corless CL, Zaman A, Sasaki A, Gopal DV, Rayhill SC, et al. Hepatic and cardiac iron overload among patients with end-stage liver disease referred for liver transplantation. *Clin Transplant* 2010;24:643-651.
36. Ludwig J, Hashimoto E, Porayko MK, Moyer TP, Baldus WP. Hemosiderosis in cirrhosis: a study of 447 native livers. *Gastroenterology* 1997;112:882-888.
37. Deugnier Y, Turlin B, le Quilleuc D, Moirand R, Loreal O, Messner M, Meunier B, et al. A reappraisal of hepatic siderosis in patients with end-stage cirrhosis: practical implications for the diagnosis of hemochromatosis. *Am J Surg Pathol* 1997;21:669-675.
38. Brandhagen DJ, Alvarez W, Therneau TM, Kruckeberg KE, Thibodeau SN, Ludwig J, Porayko MK. Iron overload in cirrhosis-HFE genotypes and outcome after liver transplantation. *Hepatology* 2000;31:456-460.
39. Yu L, Ioannou GN. Survival of liver transplant recipients with hemochromatosis in the United States. *Gastroenterology* 2007;133:489-495.
40. Fracanzani AL, Piperno A, Valenti L, Fraquelli M, Coletti S, Maraschi A, Consonni D, et al. Hemochromatosis in Italy in the last 30 years: role of genetic and acquired factors. *Hepatology* 2010;51:501-510.

**FIGURE LEGEND**

**Figure 1: Kaplan Meier survival curves of patients that received liver transplants, grouped according to the underlying liver disease. Panel A:** HH (long dot line): *HFE* related hemochromatosis, Non HH (dotted line): liver disease not related to HH. **Panel B:** HH (dotted line): Patient with HH and Hepatocellular carcinoma. HCC (plain line): patient with Hepatocellular carcinoma and liver disease other than HH. **Panel C:** ALF: Acute Liver Failure. HH: *HFE* related hemochromatosis. Alcohol: alcoholic liver disease. HCV: Hepatitis C virus related liver disease.









**Table 1:** Clinical characteristics of patients that received liver transplants to treat *HFE* hemochromatosis. LT: liver transplantation; Child-Pugh score (scale 5-15) used for assessing prognosis of chronic liver disease; HCC: Hepatocellular carcinoma.

	Age at diagnosis (years)	Age at LT (years)	Associated Liver disease	Indication for LT	Child-Pugh at LT	Survival (months) / cause of death
<b>Patient 1</b>	33	36		Biliary Hamartoma	A5	60 / Alive
<b>Patient 2</b>	54	55		HCC	A5	72 / Alive
<b>Patient 3</b>	46	55		HCC	A5	73 / Alive
<b>Patient 4</b>	47	54		HCC	A5	83 / Alive
<b>Patient 5</b>	43	54		HCC	A5	84 / Alive
<b>Patient 6</b>	39	60		HCC	B7	84 / Alive
<b>Patient 7</b>	49	60		HCC	A5	108 / Alive
<b>Patient 8</b>	45	65		HCC	A5	119 / Alive
<b>Patient 9</b>	53	53	Alcohol	HCC	A5	119 / Alive
<b>Patient 10</b>	43	56	Alcohol	HCC	A5	144 / Alive
<b>Patient 11</b>	48	59		HCC	A5	0 / Hepatic artery thrombosis, liver abscess
<b>Patient 12</b>	59	61		Liver failure	C13	1 / Sepsis (lung)
<b>Patient 13</b>	62	63	Alcohol	HCC	A5	4 / Sepsis (lung)
<b>Patient 14</b>	51	60		HCC	A5	24 / HCC recurrence
<b>Patient 15</b>	53	54	Alcohol	HCC	A5	27 / Lung cancer
<b>Patient 16</b>	44	56	Alcohol	HCC	A5	29 / Stroke
<b>Patient 17</b>	56	66		HCC	A5	78 / Lung cancer
<b>Patient 18</b>	52	55		HCC	A5	126 / Acute

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respiratory failure
/ Pulmonary
fibrosis

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**Table 2:** Clinical and biological data before and after liver transplantation (LT) in patients with HFE-related hemochromatosis (HH)

HH complication: HFE hemochromatosis-related complications. Phlebotomy: ongoing phlebotomy treatment.

RBC LT: amount of red blood cell transfusions during LT surgery. MRI: magnetic resonance imaging.

	Before Liver Transplantation						LT	After Liver Transplantation									
Patients	HH complication	Phlebotomy	Serum Ferritin (µg/L)	Transferrin saturation (%)	Serum Hepcidin (nmol/L)	Hepcidin / ferritin ratio	RBC LT	Phlebotomy	Time to Re evaluation (month)	Serum ferritin (µg/L)	Serum Iron (µmol/L)	Transferrin saturation (%)	Serum hepcidin (nmol/l)	Hepcidin / ferritin ratio	MRI		Co morbidities
															Liver Iron content	Spleen iron content	
1	Fatigue	Yes	8.6	10.5	0.9	10.46	0	No	35	10.7	14	18.7	3.94	36.8	<40 µmol/g	Normal	Dyslipidemia
2	No	Yes	1178	87.4	0.36	0.03	4	Yes /4-5 months	47	129.2	14.3	34.3	8.96	6.9	<40 µmol/g	Normal	No
3	Arthropathy, Diabetes	Yes	148	85,0	5,38	3,63	0	No	Patient refused iron metabolism study								
4	No	No	3364	89.7	8.96	0.26	9	No	58	201.3	17.5	34.0	9.68	4.8	<40 µmol/g	Normal	Diabetes
5	Arthropathy, Diabetes	Yes	31.5	19.0	2.33	7.39	0	No	60	228.1	22.2	37.9	26.17	11.4	<40 µmol/g	Normal	Diabetes, Dyslipidemia
6	Diabetes	Yes	21.9	16.6	0.18	0.82	12	No	62	175.3	16.6	27.7	11.12	6.3	<40 µmol/g	Normal	Hypertension, Diabetes
7	Arthropathy	Yes	49.1	26.9	0.18	0.36	4	No	86	163.5	13.9	27.1	14.34	8.7	<40 µmol/g	Normal	No
8	None	Yes	69.1	75.2	0.18	0.26	8	No	89	588.7	9.85	26.4	23.84	4.0	180 µmol/g	Iron overload +++	Hereditary spherocytosis unmasked after LT : Hb 7-10 g/dl
9	Diabetes	Yes	1129	79.7	0.72	0.06	3	No	92	380	16	29.0	20.8	5.4	70 µmol/g	Slight iron overload	Hypertension, excessive alcohol consumption
10	Diabetes	Yes	64.3	71.4	5.0	7.80	3	No	109	280	21.3	45.8	21.33	7.6	<40 µmol/g	Normal	Hypertension
11	Diabetes	Yes	No sample available				4	No	Patient died before re-evaluation								
12	No	Yes	564,8	89,4	0,7	0,12	17	No	Patient died before re-evaluation								
13	No	Yes	3908	89,6	3,97	0,10	4	No	Patient died before re-evaluation								
14	No	Yes	181,6	84,0	3,54	1,95	7	No	Patient died before re-evaluation								
15	Fatigue	Yes	3507	88,6	12,2	0,34	0	No	6	150	15.43	32.1	14.8	9.89	Not available	No	No

16	Diabetes	Yes	No sample available				4	No	10	79,83	18	28,1	3,4	4,26	Not available	No	No
17	None	Yes	101.3	34.3	0.18	0.17	0	No	57	170.4	10.2	19.7	13.27	7.7	<40 $\mu\text{mol/g}$	Iron overload	Hypertension, Diabetes, Dylipidemia
18	Arthropathy, diabetes	Yes	91.3	52.0	7.35	8.05	2	No	123	17.3	6.14	12.8	0.39	2.2	<40 $\mu\text{mol/g}$	Normal	Diabetes, Hypertension, Pulmonary fibrosis

