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ABSTRACT

Background & Aims

Liver stiffness measurement (LSM) by vibration-controlled transient elastography (VCTE) was shown to predict outcomes of primary biliary cholangitis (PBC) in small-size studies. We aimed to validate the prognostic value of LSM in a large cohort study.

Methods

We performed an international, multicentre, retrospective follow-up study of 3985 patients with PBC seen at 23 centres in 12 countries. Eligibility criteria included at least one reliable LSM by VCTE and a follow-up ≥ 1 year. Independent derivation (n=2740) and validation (n=568) cohorts were built. The primary endpoint was time to poor clinical outcomes defined as liver-related complications, liver transplantation, or death. Hazard ratios (HRs) with confidence intervals (CIs) were determined using a time-dependent multivariable Cox regression analysis.

Results

LSM was independently associated with poor clinical outcomes in the derivation (5324 LSMs, mean follow-up 5.0 ± 3.1 yrs.) and validation (1470 LSMs, mean follow-up 5.0 ± 2.8 yrs.) cohorts: adjusted HRs (95%CI) per additional kPa were 1.040 (1.026–1.054) and 1.042 (1.029–1.056), respectively ($p<0.0001$ for both). Adjusted C-statistics (95%CI) at baseline were 0.83 (0.79–0.87) and 0.92 (0.89–0.95), respectively. Between 5 and 30 kPa, the log-HR increased as a monotonic function of LSM. The predictive value of LSM was stable in time. LSM improved the prognostic ability of biochemical response criteria, fibrosis scores, and prognostic scores. The 8-kPa and 15-kPa cut-offs optimally separated low, medium, and high-risk groups. Forty percent of patients were at medium to high risk according to LSM.

Conclusions

LSM by VCTE is a major, independent, validated predictor of PBC outcome. Its value as a surrogate endpoint for clinical benefit in PBC should be considered.

HIGHLIGHTS

- Although recommended by clinical practice guidelines for the assessment and monitoring of primary biliary cholangitis (PBC), liver stiffness measurement (LSM) by vibration-controlled transient elastography (VCTE) has not yet been validated as a relevant predictive marker of poor clinical outcome in this disease.
- In this large international study of LSM by VCTE in PBC (> 3,000 patients), LSM improved prediction of survival beyond established biochemical response criteria and prognostic scores and its prognostic value was externally validated.
- The thresholds of 8 kPa and 15 kPa optimally discriminated patients into low, medium, and high-risk groups. Forty percent of patients were at medium to high risk of poor clinical outcomes according to these thresholds.
- LSM by VCTE is a major, validated prognostic marker of PBC. Whether it can be used in trials as a surrogate endpoint for clinical benefit should be considered.

LAY SUMMARY

Serum levels of bilirubin and alkaline phosphatase are the only surrogate markers approved by regulatory authorities to assess patients with PBC in therapy trials. Liver histology has been shown to improve prediction of survival beyond these markers but liver biopsy is a potentially harmful, invasive procedure and a serious obstacle to clinical trial recruitment. In the present large, international retrospective cohort study, liver stiffness assessed by vibration-controlled transient elastography was validated as one of the strongest predictive factors of poor clinical outcome in PBC and was shown to improve the prognostic ability of established biochemical markers of treatment response. Studies to evaluate the prognostic impact of LSM changes over time are needed to determine whether LSM can be used as a new surrogate end point for PBC.

ABBREVIATIONS

ALP, alkaline phosphatase.

ALT, alanine aminotransferase.

AST, aspartate aminotransferase.

CI, confidence interval.

GGT, gamma-glutamyl transpeptidase.

HR, hazard ratio.

LSM, liver stiffness measurement.

LT, liver transplantation.

MELD, model for end-stage liver disease.

PBC, primary biliary cholangitis.

UDCA, ursodeoxycholic acid.

VCTE, vibration-controlled transient elastography.

INTRODUCTION

Primary biliary cholangitis (PBC) is a slowly progressive, autoimmune cholestatic liver disease that, if undertreated, eventually leads to cirrhosis and its life-threatening complications [1]. Ursodeoxycholic acid (UDCA), the current universal standard-of-care therapy for PBC [2-4], is associated with prolonged liver transplantation (LT)-free survival, regardless of the disease stage and the observed biochemical response [5]. Nevertheless, the patients with PBC (approximately one-third) with no complete response to UDCA, mainly due to persistent elevated levels of alkaline phosphatase (ALP) or bilirubin after 12 months of treatment, remain at high risk of poor long-term clinical outcome [6, 7]. These patients are currently considered candidates for second-line therapies, whether available in routine care in a label (obeticholic acid) or off-label (fibrates) use or still under clinical investigation in trials, in association with UDCA therapy [8, 9].

Because PBC is a very slow chronic disease, liver biochemical tests are used as primary surrogate endpoints for mortality or need for LT in most ongoing clinical trials [10]. Yet, the predictive ability of such biochemical endpoints is only partial and their prognostic value in the specific context of combination therapies not fully established. Therefore, the development and validation of new surrogate markers of the disease that could be used in combination with biochemical response as substitutes for clinical outcomes appear as a necessary condition for a better evaluation of therapeutic strategies for PBC [11, 12]. In this regard, the need to incorporate fibrosis stage into PBC risk stratification systems has recently been proposed since assessment of fibrosis stage was shown to grant prognostic value beyond biochemical response to treatment [13]. These findings strongly support the inclusion of non-invasive markers of fibrosis in all future prognostic tools developed for PBC.

The introduction of vibration-controlled transient elastography (VCTE) using FibroScan® in 2003 has revolutionized the evaluation of liver diseases [14]. Today, of the various alternative techniques of liver elastography, VCTE remains one of the most popular and widely used worldwide [15]. Liver stiffness measurement (LSM) by VCTE has indeed been shown as a very simple and reliable means for diagnosing cirrhosis or advanced fibrosis in many chronic liver diseases, including PBC [16, 17]. It has further been linked to the risk of portal hypertension, cirrhotic decompensation, hepatocellular carcinoma, and liver-related mortality in different liver conditions, including PBC [16, 18-20]. However, although LSM is currently recommended by clinical practice guidelines for the assessment and monitoring of PBC [21-23], its usefulness as a reliable predictor of clinical outcome in this disease remains to be proven. In the present large-scale, international follow-up study of patients with PBC, our aim was to assess and validate the prognostic value of LSM using FibroScan® alongside those of pre-established biochemical response criteria and prognostic scores.

METHODS

Study population and Design

Between November 2019 and November 2021, we conducted an international, multicentre, retrospective cohort study under the auspices of the Global PBC Study Group and the European Reference Network (ERN) for rare hepatological diseases (Rare-Liver). A total of 23 tertiary centres from 12 countries in Europe, North America and the Middle East participated in the study. Unrelated derivation and validation cohorts were consecutively built, including a total of 3284 and 701 patients with PBC, respectively. The contribution of each participating centre to the constitution of these original data sources is shown in **Table S1**.

All patients had a diagnosis of PBC established according to international guidelines [2, 4]. To be eligible for analysis, patients had to have at least one reliable VCTE measurement using FibroScan® and a minimum of one year of subsequent FU. All available LSMs in a single patient could be collected, regardless of the probe (M or XL) used. A reliable LSM was defined by at least 10 valid measurements with an interquartile/median ratio ≤ 30% according to the manufacturer's recommendations and usual definition [14, 24]. All unreliable LSMs were excluded from analysis. Patients with a history of LT or cirrhotic complication before first LSM were excluded, as well as those with a history of autoimmune hepatitis overlap syndrome or corticosteroid and/or immunosuppressive long-term therapy.

Blood test results within 2 months of LSMs were collected when available. We considered as explanatory variables those previously shown to predict survival in PBC and those judged to be clinically-relevant, including age, sex, serum bilirubin and albumin, ALP, aspartate aminotransferase (AST), alanine aminotransferase (ALT), gamma-glutamyl transpeptidase (GGT), platelet count, international normalized ratio, serum creatinine, histological stage, and concomitant treatment with UDCA, obeticholic acid, and/or fibrates. The Globe, UK-PBC, MELD, and FIB-4 scores were calculated whenever possible [25-28]. Because most patients were included several years after the start of treatment, the Globe and UK-PBC scores were calculated considering LSM date as at 1 year of treatment. Biochemical response to treatment was defined according to the Paris-2, Toronto, and Globe criteria using the same rule of date than for prognostic scores [6, 25, 29].

The study entry was the date of the first reliable LSM available. The time between the date of entry and the occurrence of a clinically-significant event was calculated. Poor clinical outcomes were defined as death, LT or registration on the liver transplant waiting list, or complication of cirrhosis, including variceal bleeding, ascites, hepatic encephalopathy, or

hepatocellular carcinoma, when no death or LT was reported at time of last follow-up. The patients who did not experience any of these events were censored at the date of last known visit.

The study was conducted in accordance with the Declaration of Helsinki. It was a retrospective observational analysis based on previously collected routine care data with no opposition by patients. The protocol was approved by the institutional research board of each participating centre in accordance with their local regulations.

Statistical Analysis

We conducted a multivariable survival analysis using LSM and biochemical covariates as time-dependent variables. The primary endpoint of the study was survival without poor clinical outcomes, including death, LT, or liver complications as defined above. This endpoint was assessed in the derivation and validation cohorts using a time-dependent, multivariable-adjusted Cox proportional-hazards model. For each covariate analyzed, the association with the primary endpoint was expressed as a hazard ratio (HR) with 95% confidence interval (CI). To explore the shape or log-linearity of the association between LSM and the HR of poor clinical outcome, we estimated a Cox model with a smooth transformation of LSM at baseline using cubic B-spline with 4 equally spaced knots. Several sensitivity analyses on different subpopulations of patients were performed: 1) patients treated with UDCA monotherapy beyond 12 months (exclusion of patients who received second-line therapy, including fibrates, obeticholic acid, or corticosteroids; exclusion of LSMs performed before 12 months of UDCA), 2) patients assessed using FibroScan® M probe only (exclusion of LSMs performed with XL probe). The predictive performance of LSM was evaluated at baseline using Harrell's C-index and time-dependent receiver operating characteristic (ROC) curve analysis [30]. Inverse

probability of censoring weighting was used to calculate area under the ROC curves (AUROC) as a function of time. Using bivariate models, the prognostic ability of LSM was individually faced with those of the Paris-2, Toronto, and Globe criteria of biochemical response, as well as those of the Globe, UK-PBC, MELD, APRI, and FIB-4 scores. Comparison of Harrell's C-indices was performed using a non-parametric bootstrap approach with 500 replicates [31]. The thresholds of LSM and Globe score that best discriminated patients into low, medium, and high-risk groups for poor clinical outcomes were determined from the derivation cohort using an unbiased grid search method with 2 cut-offs and optimal model selection based on log-likelihood [32]. For simplicity, the LSM thresholds were rounded to the nearest whole number. Risk heat maps for poor clinical outcomes were generated at different time points of follow-up from LSM and Globe score values at baseline. The goodness-of-fit of the prognostic model was assessed using a Poisson regression model applied to the validation cohort [33]. Survival rates were determined using the Kaplan-Meier or Cox estimates. P-values < 0.05 were considered significant. All statistical analyses were performed using SAS version 9.4 (SAS corporation).

RESULTS

Baseline Characteristics

The flow chart of the study is shown in **Figure S1**. Of the 3985 patients initially registered, of which 3284 and 701 were in the derivation and validation cohorts, respectively, 3308 (83%) were eligible for analysis, of which 2740 (83%) were in the derivation cohort and 568 (81%) in the validation cohort. Of the 6859 and 1656 LSMs registered in the derivation and validation cohorts, respectively, 1044 (15.2%) and 148 (8.9%) were missing (supposedly failed) or unreliable. The total number of LSMs available for analysis was 5324 (median per patient 2,

range 1 – 5) in the derivation cohort and 1470 (median per patient 2, range 1 – 8) in the validation cohort. In patients with ≥ 2 LSMs, the mean time between consecutive LSMs was 2.3 ± 1.5 years and 1.7 ± 1.4 years, respectively. The entry characteristics of patients in both cohorts are shown in **Table 1**. Disease characteristics, such as serum levels of total bilirubin and transaminases, LSM, APRI and FIB-4 scores, or the percentage of patients with cirrhosis or advanced fibrosis, indicated more severe disease at baseline in the validation cohort than in the derivation cohort.

Treatment and Disease Outcome

As expected, the vast majority of patients (> 90%) were treated with UDCA (more than 50% at entry received UDCA for > 1 year), while second-line therapy with obeticholic acid or fibrates at any time of follow-up was reported in approximately 20% (18.0% in the derivation cohort, 22.2% in the validation cohort). The mean follow-up was 5.0 ± 3.1 years (median 4.1 years, IQR 2.5 – 6.9 years, range 1.0 – 16.4 years) in the derivation cohort and 5.0 ± 2.8 years (median 4.5 years, IQR 2.7 – 6.3 years, 1.0 – 15.7 years) in the validation cohort. The rates of all-cause and liver-related deaths and of liver complications without subsequent death/LT at time of last follow-up were comparable between cohorts, but LT was more frequently observed in the validation cohort than in the derivation cohort, which is consistent with more advanced disease in the former cohort (**Table 1**). In total, 274 (10.1%) patients in the derivation cohort and 82 (14.4%) in the validation cohort reached the primary endpoint. The 5-, 10-, and 15-year survival rates without LT or liver complications were 93.5%, 81.3%, and 49.3%, respectively in the derivation cohort, and 87.5%, 75.3%, and 42.6%, respectively in the validation cohort (p-value for log-rank test < 0.0001, **Figure 1**).

Association of LSM with Disease Outcome

In a time-dependent univariate analysis, LSM was significantly associated with poor clinical outcomes in both the derivation (HR per kPa added 1.065, 95% CI 1.057 – 1.074, p<0.0001) and validation (HR per kPa added 1.061, 95% CI 1.050 – 1.071, p<0.0001) cohorts. Between 5 and 30 kPa, the log hazard of clinical outcomes increased as a monotonic function of LSM (**Figure 2A**). In a time-dependent, multivariable analysis within the derivation cohort, including age, sex, and known prognostic factors such as total bilirubin, albumin, ALP, AST, and platelet count, LSM was the covariate most strongly associated with poor clinical outcomes (**Table 2**). This result was replicated in the validation cohort (**Table S2**) and remained true even when the analysis was restricted to patients treated with UDCA only and to LSMs beyond 1 year of treatment (**Table S3**). Excluding the measurements obtained with the XL probe (n=682) did not affect the results either (**Table S4**).

Predictive Ability of LSM

At baseline, the adjusted Harrell's C-index (95% CI) for LSM was 0.8305 (0.7933 – 0.8677) in the derivation cohort and 0.9181 (0.8895 – 0.9467) in the validation cohort. When analysed using a time-dependent ROC curve analysis, the predictive ability of baseline LSM for poor clinical outcomes was stable over years (**Figure 2B**). The prognostic performance at baseline of the biochemical response criteria (Paris-2, Toronto, and Globe), fibrosis scores (APRI, FIB-4) and prognostic scores (Globe, UK-PBC, and MELD) were determined both individually and alongside LSM in the derivation (**Table 3**) and validation (**Table S5**) cohorts. LSM significantly added to the performance of these predictors at baseline. In a time-dependent bivariate analysis, LSM showed independent predictive value as compared to each predictor (**Table S6**).

As the Globe score had the second highest predictive value after LSM, it was chosen as the main competitor of LSM for the rest of the study.

LSM and Biochemical Predictors Interactions

Interactions between LSM and biochemical predictors were evaluated both semi-quantitatively and continuously. In the derivation cohort, the thresholds that optimally separated patients at baseline into low-, medium-, and high-risk groups were 8 kPa and 15 kPa for LSM, and 0.5 and 1.8 for the Globe score ($p<0.0001$ for both, **Figure 3A**). The discriminative ability of these thresholds was confirmed in the validation cohort ($p<0.0001$ for both, **Figure 3B**). The distributions of low-, medium-, and high-risk groups based on LSM were 61.9%, 26.5%, and 11.6% in the derivation cohort and 52.1%, 29.1%, and 18.8% in the validation cohort. Those based on the Globe score were 70.5%, 24.9%, and 4.6%, and 65.8%, 26.9%, and 7.3%, respectively. Compared to low-risk group, the HRs associated with medium and high-risk groups were 3.496 (95%CI 2.412 – 5.069) and 15.677 (95%CI 10.878 – 22.592), respectively for LSM and 4.157 (95%CI 3.013 – 5.734) and 24.720 (95%CI 16.773 – 36.430), respectively for the Globe score. LSM thresholds were able to separate patients into risk groups irrespective of age category (≤ 45 years vs. > 45 years; **Figure S2**). Considered together, LSM and Globe score thresholds provided a more accurate stratification of patients into risk subgroups (**Figure 4A**). When a commonly-used binary criterion for biochemical response, as Paris-2 definition, was used instead of the Globe score, LSM thresholds continued to discriminate patients into significant risk groups regardless of therapeutic response (**Figure 4B**). Finally, risk heat maps for poor clinical outcomes at 1, 3, 5, and 10 years of follow-up were derived from the continuous values of LSM and Globe score at baseline (**Figure 5**). The calibration of the model was adequate with a standardized incidence ratio of observed vs.

expected events of 1.15 (95% CI, 0.92 – 1.45) (**Table S7**). The predicted probabilities of poor outcomes and 95% CI can be calculated using a web tool available at the following internet address: **https://triton.iplesp.upmc.fr/webcalculator/**.

DISCUSSION

In this study of > 3,000 patients with PBC without prior cirrhosis-related complications followed-up for an average of 5 years over the past 15 years in tertiary centres from Europe, North America or the Middle East, elevated values of LSM as assessed by VCTE (FibroScan®) were unequivocally associated with increased risk of poor clinical outcomes, including death, LT or liver complications. This association was independent of baseline and temporal prognostic factors and scores, treatment type and response, and duration of follow-up. These results were replicated in an external validation cohort. The combination of LSM with established biochemical criteria of therapeutic response or prognostic scores improved prognostic prediction for patients. Therefore, these findings confirm that LSM could be useful to evaluate and monitor PBC patients in routine care and therapeutic trials in combination with biochemical results.

The use of LSM in medical practice has developed considerably over the last 15 years [15, 34]. Among the different techniques available, VCTE (FibroScan®) was the first to be marketed, has been the most extensively evaluated, and is today one of the most popular and commonly used, especially in hepatology units [14, 35]. Prior studies in patients with PBC have shown an association of LSM with histological fibrosis stage, degree of portal hypertension, and risk of death or need for LT [16, 17, 19, 20, 36-38]. However, these results are still supported by limited data and a few small-size single-centre studies. The present study is the largest ever study of LSM value in PBC. It shows that between 5 kPa and 30 kPa, namely the

range within which most patients with PBC are seen in routine, the risk of poor clinical outcomes increases as a monotonic function of LSM, a characteristic shared with serum levels of ALP and bilirubin [7]. This indicates that the lower the LSM, the higher the survival time without poor clinical outcomes. In addition, our results show that the prognostic ability of LSM is sustained in time and across specific high-risk groups such as inadequate responders or relatively young patients. Taken together, these results strongly support the use of LSM by VCTE in the assessment and monitoring of PBC, both in routine care practice and clinical trials, in conjunction with established prognostic biochemical indices.

It has been shown that LSM values > 9.6 kPa at baseline could distinguish high- from low-risk PBC patients for clinical outcome [16]. The present study has gained in specificity in distinguishing between low, medium and high-risk patients based on the 8-kPa and 15-kPa thresholds that were determined using an unbiased method. These cut-offs correspond virtually to the diagnostic thresholds for significant fibrosis and cirrhosis, respectively, which is clinically relevant and consistent with the established prognostic value of fibrosis stage in chronic liver diseases, especially PBC [13]. The 15-kPa threshold is also in line with the Baveno VII recommendations, which suggest using >15 kPa as the threshold above which compensated advanced chronic liver disease should be strongly suspected, regardless of aetiology [23]. Medium- and high-risk patients, who should be prioritized for clinical trials, represented approximately 40% of the whole cohort. These patients showed approximately 4-fold and 16-fold higher risk of poor clinical outcomes, respectively, as compared to low-risk patients. While the 10-year rate of clinical events in low-risk patients did not exceed 20%, it varied between 20% and 50% in medium-risk patients, and between 50% and 90% in high-risk patients, particularly in relation to the biochemical response.

Second-line therapy for PBC (obeticholic acid or fibrates) is currently recommended in patients with an inadequate biochemical response to UDCA, regardless of disease stage [2-4]. Over the last 10 years, several definitions of inadequate biochemical response have been proposed, of which the Paris-2, Toronto, and Globe score-based definitions are among the best known [6, 25, 29]. The present study shows that LSM provides prognostic information in PBC beyond biochemical response, regardless of the definition used. This should prompt future recommendations for PBC therapy to integrate LSM in decision-making algorithms. Indeed, even adequate responders to UDCA could be legitimate candidates for second-line therapy if a medium or high probability of clinical events is predicted by LSM, considering that any 10-year rate of clinical events above 20% in a middle-aged population is a poor outcome.

The fact that in the present study LSM was shown as the variable most strongly associated with long-term outcomes in PBC, ahead ALP and bilirubin levels, suggests that it might be used in therapy trials as a surrogate endpoint for survival. This is supported by the results of the recent phase 3 BEZURSO (bezafibrate for PBC with inadequate response to UDCA) trial, a 2-year double-blind, randomized study in which LSM was shown to increase significantly in patients assigned to the placebo group, whereas it remained stable or even decreased in those assigned to the bezafibrate group [9]. This suggests two key points: 1) progression of LSM is expected in UDCA-resistant patients; 2) a pharmacological treatment can slow, stop, or even reverse this course. Consequently, a primary composite endpoint defined by a clinically-relevant biochemical response (ideally, normalisation of ALP and bilirubin) and no concomitant increase in LSM might appear to be a realistic target that could become the new standard for PBC trials in UDCA-resistant patients. Further studies, however, are needed to characterise the temporal evolution of LSM in different risk groups of PBC

patients, and specifically the inter- and within-patient variability of this measure over time. These repeated measures analyses are currently underway.

There are some limitations to the present study. The derivation and validation cohorts were created consecutively from different periods and centers. This could explain the differences observed in the severity of the two cohorts at baseline, as well as in long-term clinical outcomes, despite the same selection and exclusion criteria used. Finding additional LSM data for validation was difficult because the derivation cohort was assembled from the main leading PBC expert centers equipped with FibroScan®. This may have introduced a selection bias in the validation cohort in that, especially in smaller, less PBC-focused centers, FibroScan® may be used primarily in patients with more advanced disease. The study was not conducted on an intent-to-predict basis and was limited to LSM results considered reliable and interpretable according to the manufacturer's recommendations and usual definition [14, 24]. On the overall cohorts, 1192 (13.9%) out of 8515 LSMs were unreliable or failed, which is consistent with data from other large studies in other chronic liver diseases [39, 40]. This rate of about 10%-15% of unreliable or failed results with this elastography technique (VCTE) should be kept in mind, especially if LSM is considered as an endpoint for assessing therapy strategies. The use and follow-up policies of LSM were not uniform across centres and were probably biased by the fact that clinicians are more likely to assess and repeat LSM in symptomatic patients and/or with more advanced disease. However, we used a time-dependent multivariable-adjusted analysis in order to minimize the potential impact of population and follow-up heterogeneity between centres, and a large number of patients with low LSM at baseline was followed over time with repeated measurements.

In conclusion, in the largest ever study of LSM in patients with PBC, we show that LSM assessed by VCTE improves prediction of survival beyond biochemical response, established

prognostic scores, and age categories, independent of time. A significant proportion (40%) of PBC patients are at medium or high risk of poor clinical outcome according to LSM. This robust analysis suggests that LSM can reasonably be regarded as useful prognostic marker and a potential surrogate endpoint in PBC clinical trials.

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Table 1. Entry and follow-up characteristics of patients

Characteristics	Derivation cohort (n=2740)	Validation cohort (n=568)
Year at entry	2013.9 ± 3.3	2012.5 ± 5.2
Age at entry (year)	57.9 ± 11.7	55.3 ± 12.3
Age at diagnosis (year)	51.8 ± 12.0	52.1 ± 12.1
Female Sex (yes)	2496 (91.1%)	509 (89.6%)
Body mass index ($kg.m^{-2}$)	26.2 ± 6.3	25.1 ± 4.7
Obesity (yes)	546 (19.9%)	80 (14.1%)
Total Bilirubin (µmol/l)	11.4 ± 13.1	15.5 ± 22.0
ALP (xULN)	1.8 ± 8.2	1.9 ± 1.4
ALT (xULN)	1.2 ± 1.1	1.7 ± 1.9
Albumin (g/l)	41.8 ± 3.8	41.8 ± 4.3
Platelet count (G/l)	252.8 ± 79.3	243.8 ± 88.5
LSM (kPa)	9.5 ± 9.0	11.7 ± 11.9
XL probe (yes)	351 (12.8%)	74 (13.0%)
APRI score	0.55 ± 0.57	0.73 + 0.77
FIB-4 score	1.64 ± 1.25	1.87 ± 1.73
Advanced fibrosis* (yes)	660 (24.1%)	183 (32.3%)
Cirrhosis* (yes)	434 (15.8%)	130 (22.9%)
UDCA (at any time)	2704 (98.7%)	550 (96.8%)
UDCA at entry ≥ 1 year (yes)	1696 (61.9%)	302 (53.2%)
Obeticholic acid (at any time)	208 (7.6%)	43 (7.6%)
Fibrates (at any time)	362 (13.2%)	90 (15.9%)
Follow-up time (year)	5.0 ± 3.1	5.0 ± 2.8
No. of LSM per patient	2.1 ± 1.1	2.4 ± 1.3
All-cause death (yes)	145 (5.3%)	26 (4.6%)
Liver-related death (yes)	62 (2.3%)	13 (2.3%)
Liver transplantation (yes)	56 (2.0%)	39 (6.9%)
Liv. compl. wo LT/death (yes)	77 (2.8%)	17 (3.0%)

*Advanced fibrosis was defined by histological stage 3-4 or LSM > 10.7 kPa [16]. Cirrhosis was defined by histological stage 4, LSM > 16.9 kPa [16], or platelet count < 150000 G/l. UDCA, ursodeoxycholic acid.

Table 2. Time-dependent, multivariable-adjusted Cox regression analysis for poor clinical outcomes (derivation cohort, 2740 patients, 5324 LSMs)

Parameter	Estimate	Chi^2	HR (95% CI)	P-value
LSM (kPa)	0.0394 ± 0.0068	33.60	1.040 (1.026 – 1.054)	< 0.0001
ALP (xULN)	0.1996 ± 0.0461	18.77	1.221 (1.116 – 1.336)	< 0.0001
Platelets (G/l)	-0.0059 ± 0.0016	14.71	0.994 (0.991 – 0.997)	0.0001
Age (year)	0.0313 ± 0.0093	11.42	1.032 (1.013 – 1.051)	0.0007
Albumin (g/l)	-0.0471 ± 0.0140	11.39	0.954 (0.928 – 0.980)	0.0007
T. Bilirubin (µM/l)	0.1458 ± 0.0680	4.60	1.157 (1.013 – 1.322)	0.03
Male sex (yes)	0.3966 ± 0.2515	2.49	1.486 (0.908 – 2.433)	0.11
AST (xULN)	0.0316 ± 0.0955	0.11	1.032 (0.856 – 1.245)	0.74

Parameters are sorted by decreasing order of statistical significance. Poor clinical outcomes are defined by death, LT or liver complications.

Table 3. Added value of LSM to prognostic scores, fibrosis scores, and biochemical response criteria in predicting poor clinical outcomes in PBC

	Harrell's C-index (95% CI) unadjusted for LSM	Harrell's C-index (95% CI) adjusted for LSM	P-value
Globe score	0.7977 (0.7603 – 0.8351)	0.8322 (0.7952 – 0.8692)	0.0004
UK-PBC score	0.7469 (0.7028 – 0.7910)	0.7956 (0.7527 – 0.8385)	<0.0001
MELD score	0.7774 (0.7347 – 0.8201)	0.8314 (0.7959 – 0.8669)	0.0334
APRI score	0.7767 (0.7401 – 0.8134)	0.8253 (0.7904 – 0.8602)	<0.0001
FIB-4 score	0.7885 (0.7528 – 0.8242)	0.8312 (0.7961 – 0.8663)	<0.0001
Globe resp. (no)	0.7168 (0.6811 – 0.7525)	0.8178 (0.7802 – 0.8554)	<0.0001
Toronto resp. (no)	0.6591 (0.6258 – 0.6924)	0.8073 (0.7712 – 0.8434)	<0.0001
Paris-2 resp. (no)	0.6553 (0.6234 – 0.6872)	0.8105 (0.7744 – 0.8466)	<0.0001

Harrell's C-index reflects the probability a randomly selected patient who experienced a poor clinical outcome (death, LT, or liver complications) had a higher risk score or poorer response than a patient who had not experienced the event.

FIGURE LEGENDS

Figure 1. Probability of survival without poor clinical outcomes.

Probability of survival without poor clinical outcomes *of patients with PBC in the derivation (n = 2740, solid line) and validation (n = 568, dotted line) cohorts. Survival rates between both cohorts were significantly different (log-rank test, p<0.0001).*

Figure 2. Performance of LSM in predicting poor clinical outcomes.

*The log hazard of poor clinical outcomes as estimated using a cubic spline function of LSM at baseline (**panel A**). Predictive ability of baseline LSM for poor clinical outcomes as evaluated using a time-dependent area under receiver operating characteristic (ROC) curve analysis (**panel B**).*

Figure 3. Probability of survival without poor clinical outcomes according to LSM and Globe score risk groups at baseline.

Probability of survival without poor clinical outcomes *of patients with PBC as determined in the derivation (**panel A**) and validation (**panel B**) cohorts according to low- (thin line), medium- (mid-thick line), and high- (thick line) risk groups defined at baseline according to LSM (left diagrams) or Globe score (right diagrams) thresholds. The LSM and Globe score thresholds were determined using a grid search unbiased method. Survival probabilities were calculated using Kaplan-Meier estimates.*

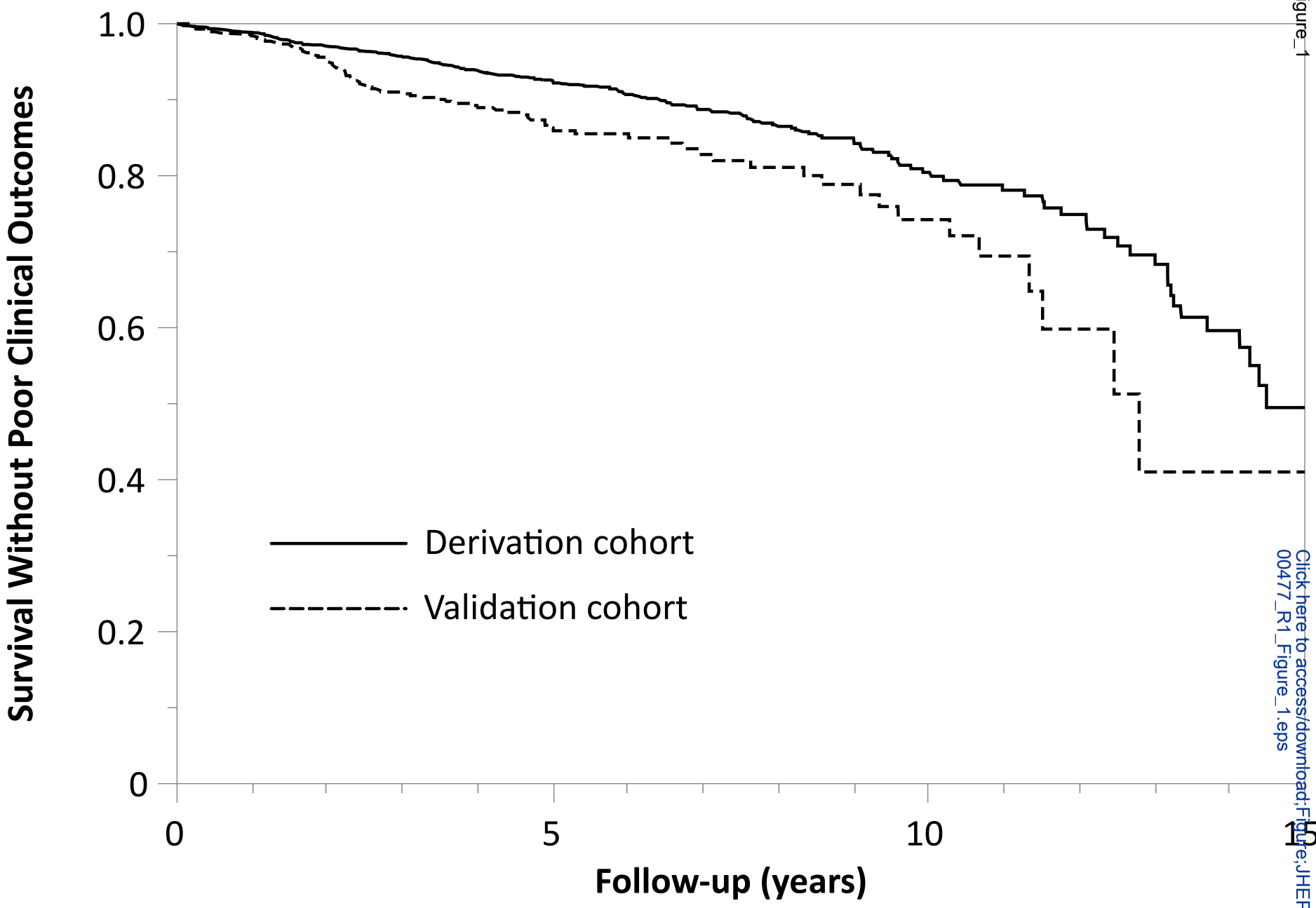
Figure 4. Probability of survival without poor clinical outcomes according to LSM and biochemical (Globe score, Paris-2 criteria) combined risk groups at baseline.

Probability of survival without poor clinical outcomes *of patients with PBC as determined in the derivation cohort according to LSM and Globe score (GS) combined risk groups (**panel A**) or LSM and Paris-2 combined risk groups (**panel B**) assessed at baseline. Survival probabilities were calculated using Cox regression estimates.*

Figure 5. Risk heat maps for poor clinical outcomes as derived at 1, 3, 5, and 10 years from the baseline values of LSM and Globe score.

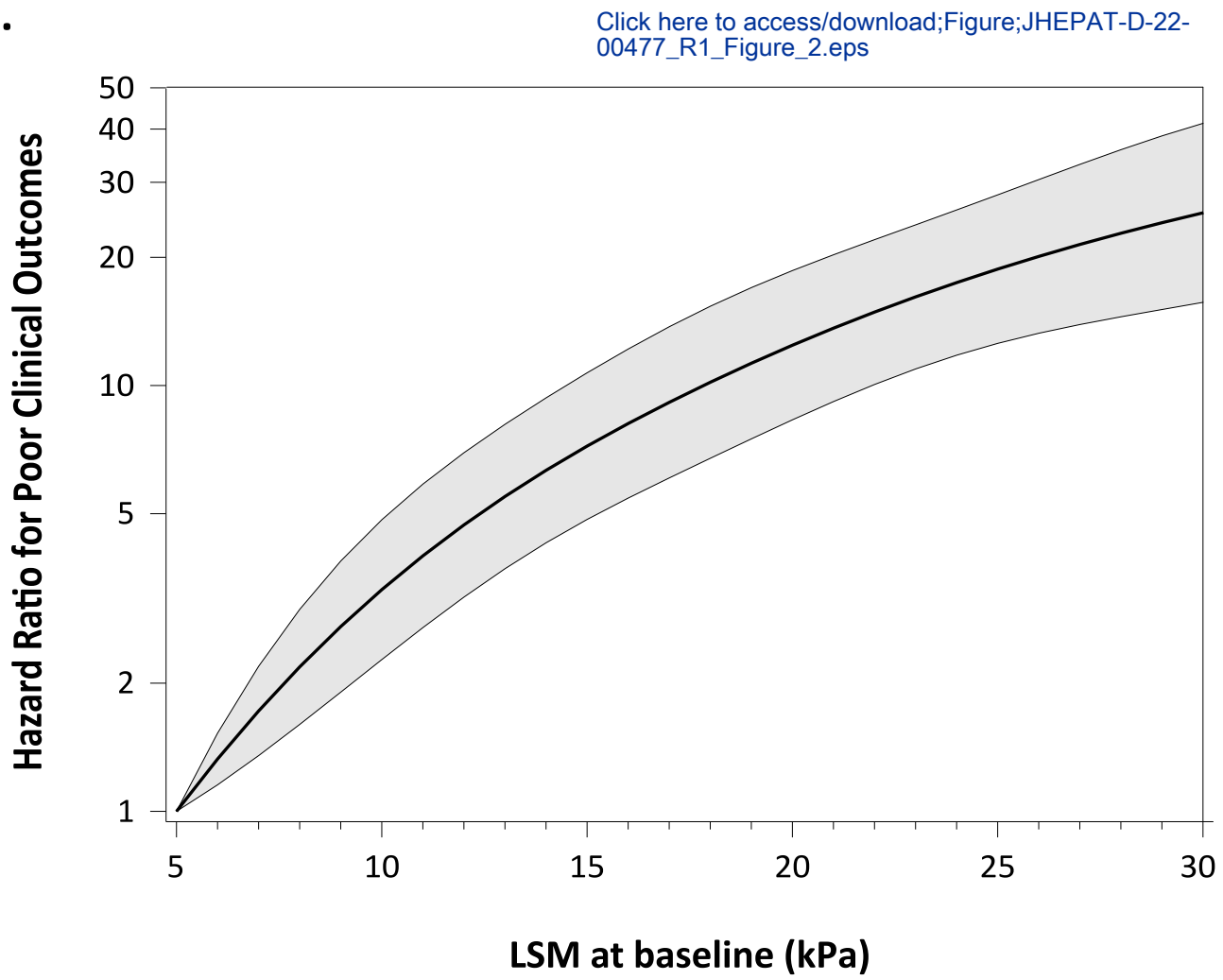
The expected probabilities of poor clinical outcomes*, i.e., liver complications, liver transplantation, or death, were calculated at different time points (1, 3, 5, and 10 years) based on the baseline values of LSM and Globe score. A continuous colour scale (y-axis shown on the left) was used to visually represent the probability level. Probabilities and 95% confidence*

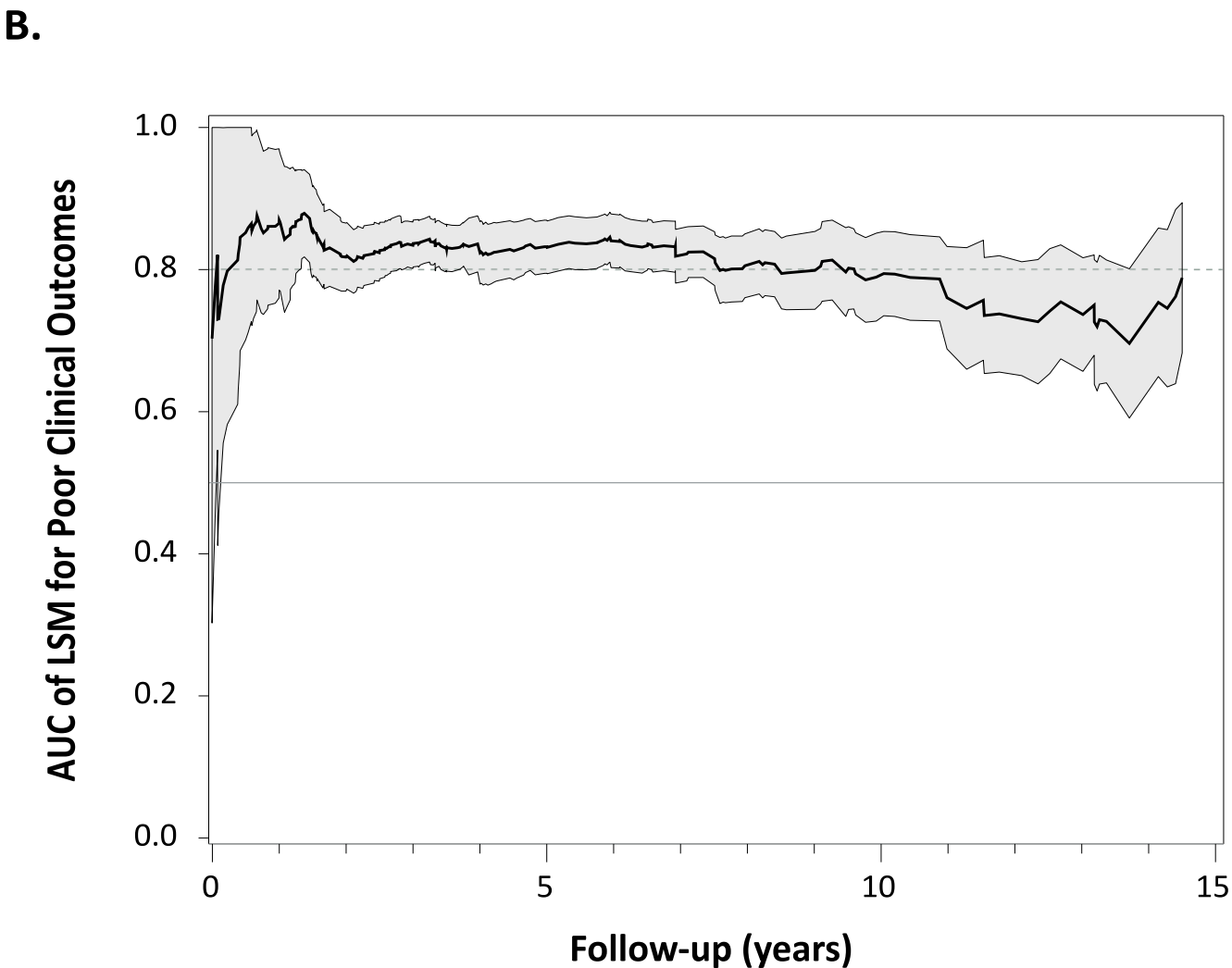
intervals can be determined using a web calculator available at the following internet address: https://triton.iplesp.upmc.fr/webcalculator/.



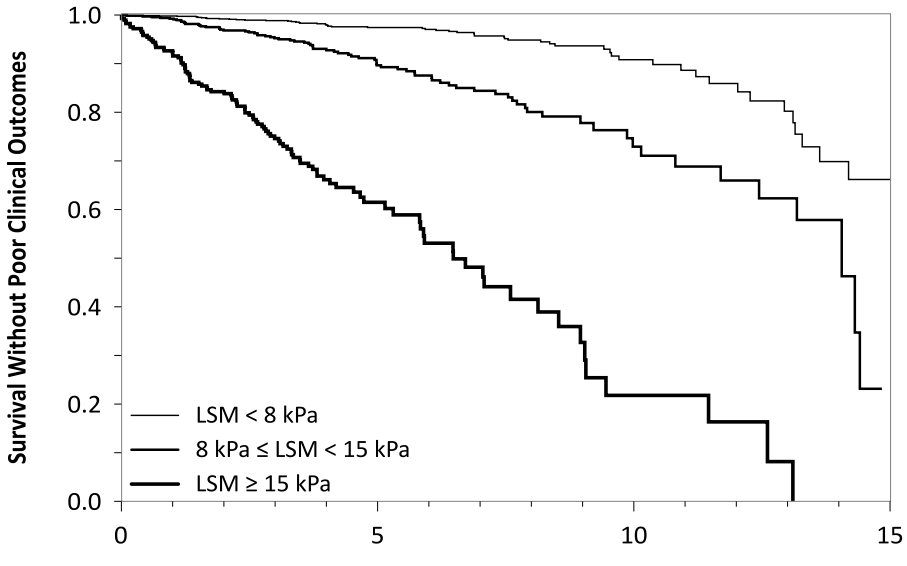
Patients at risk				
Derivation cohort	2740	1096	217	19
Validation cohort	568	240	39	2

Figure_2

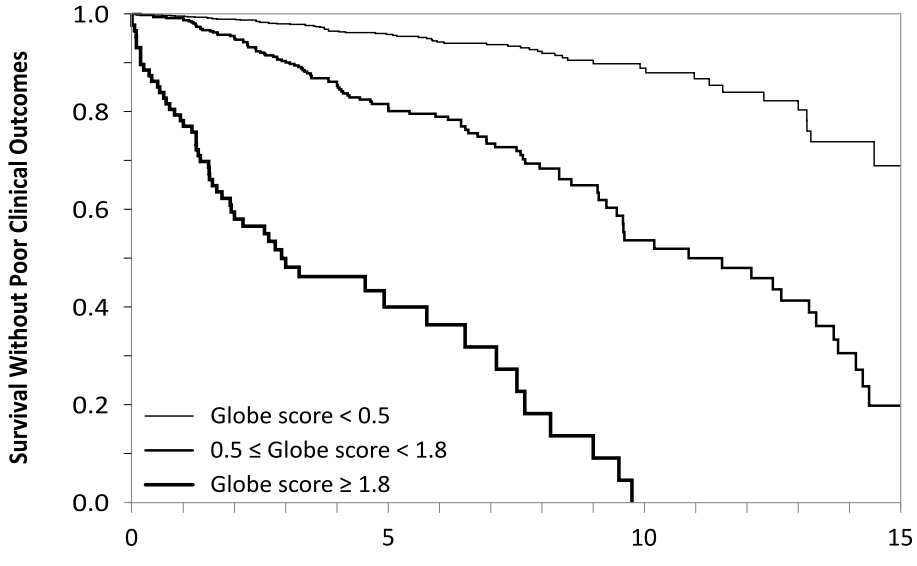




A. Derivation cohort

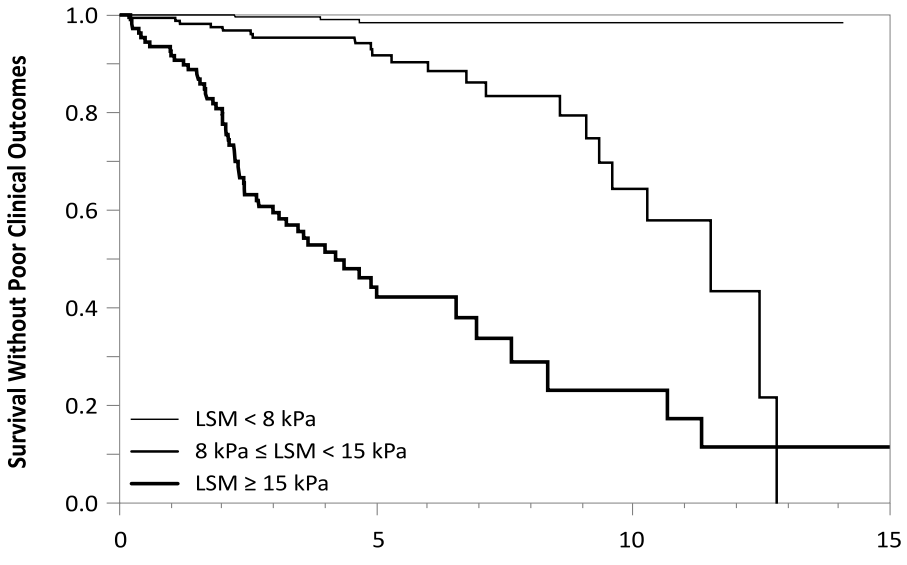


Patients at risk				
Low risk	1502	624	107	5
Medium risk	676	243	43	0
High risk	292	51	4	0

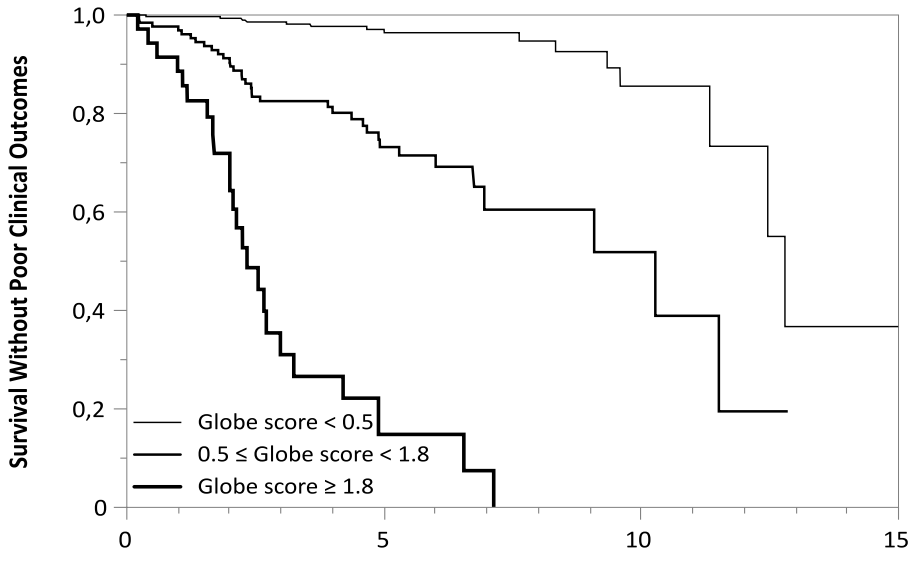


Patients at risk				
Low risk	1340	500	94	6
Medium risk	466	165	31	1
High risk	87	11	0	0

B. Validation cohort



Patients at risk				
Low risk	293	146	25	0
Medium risk	167	73	11	0
IHigh risk	108	23	5	2



Patients at risk				
Low risk	313	148	20	2
Medium risk	128	49	5	0
High risk	35	3	0	0

Figure 4

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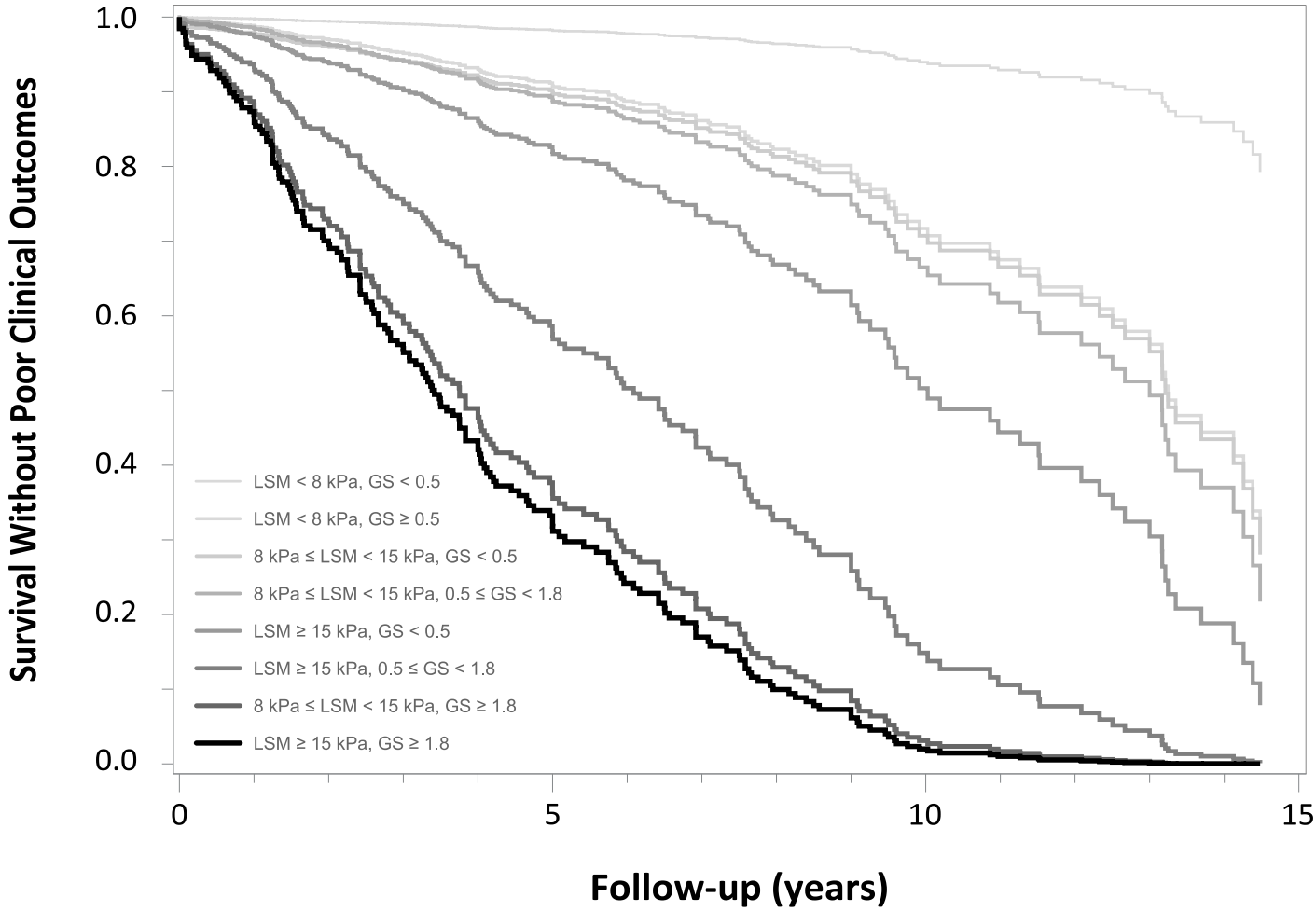
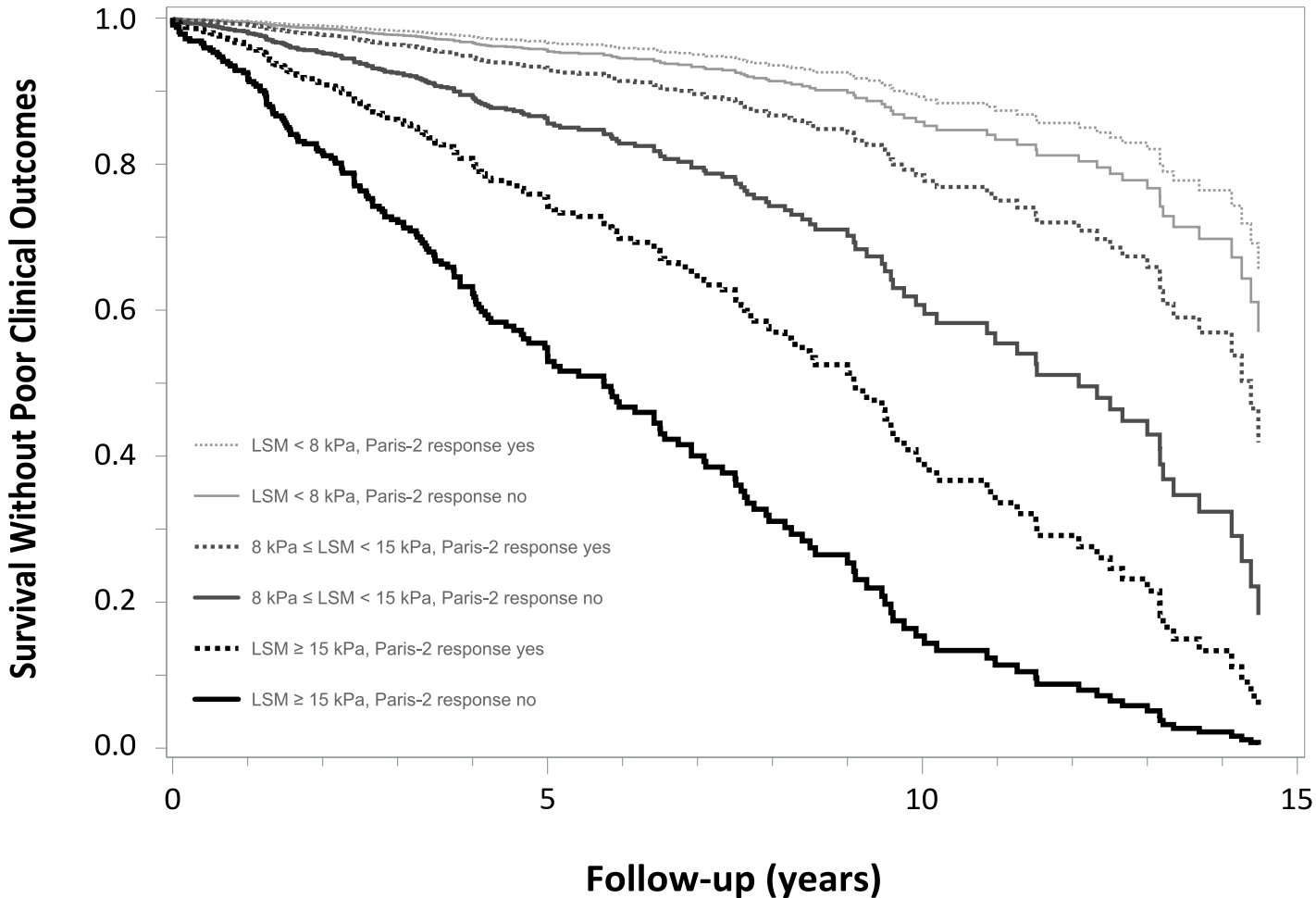
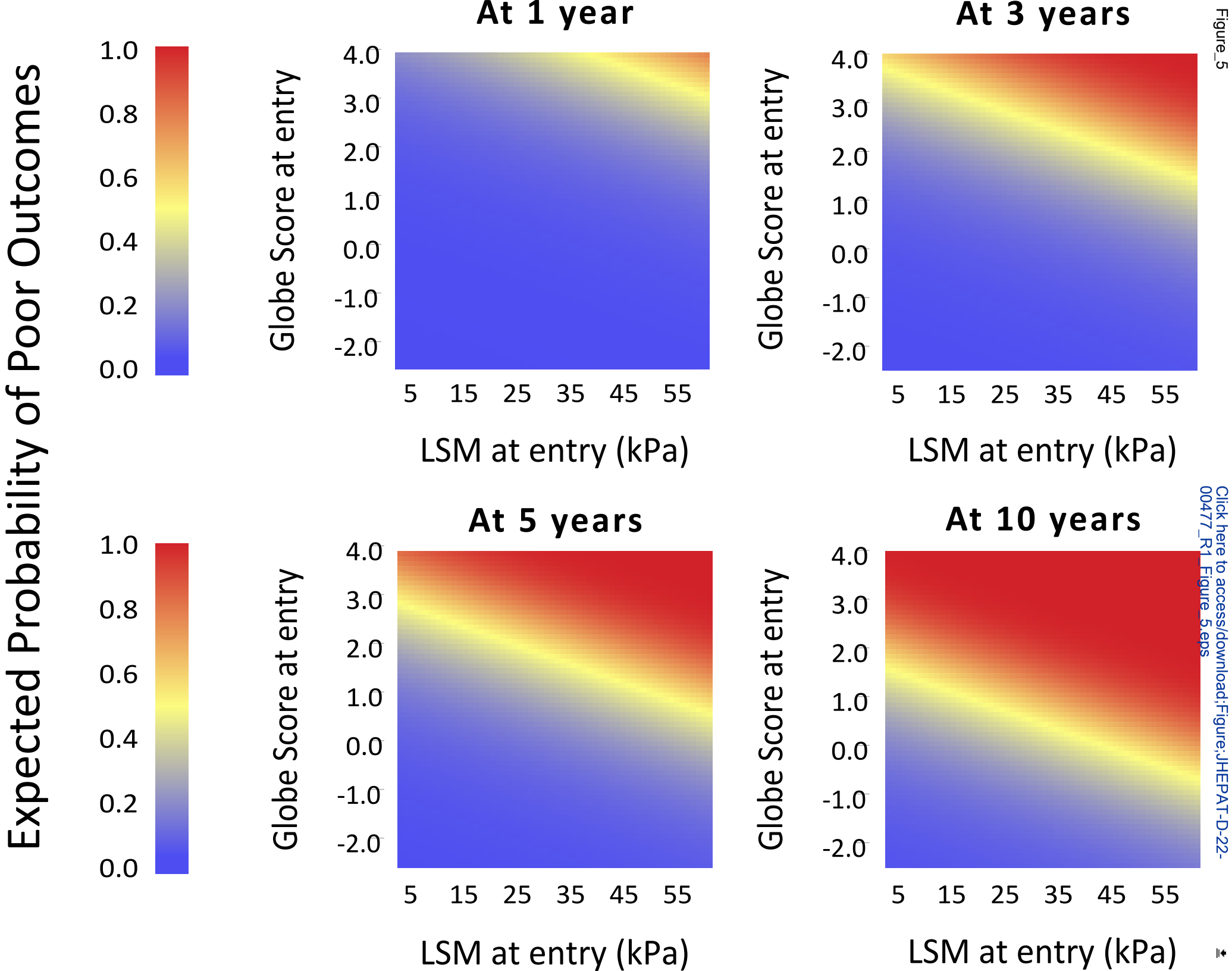
A. LSM and Globe score risk groups



B. LSM and Paris-2 risk groups





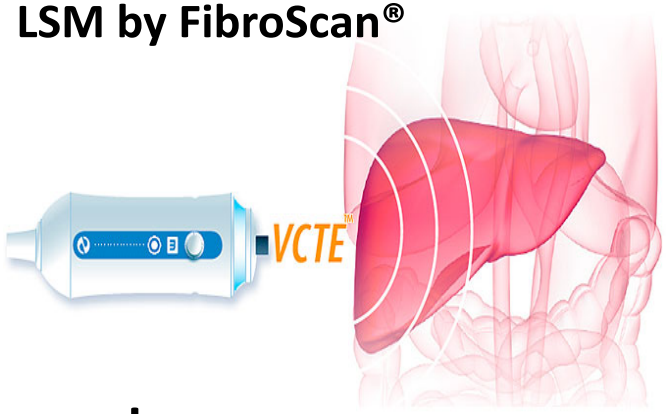
Graphical Abstract

Improving Risk Prediction in Primary Biliary Cholangitis

Combining Liver Stiffness Measurement (LSM) and Globe Score Accurately Predicts Clinical Outcomes

Derivation (2740 Patients) & Validation (568 Patients) Cohorts

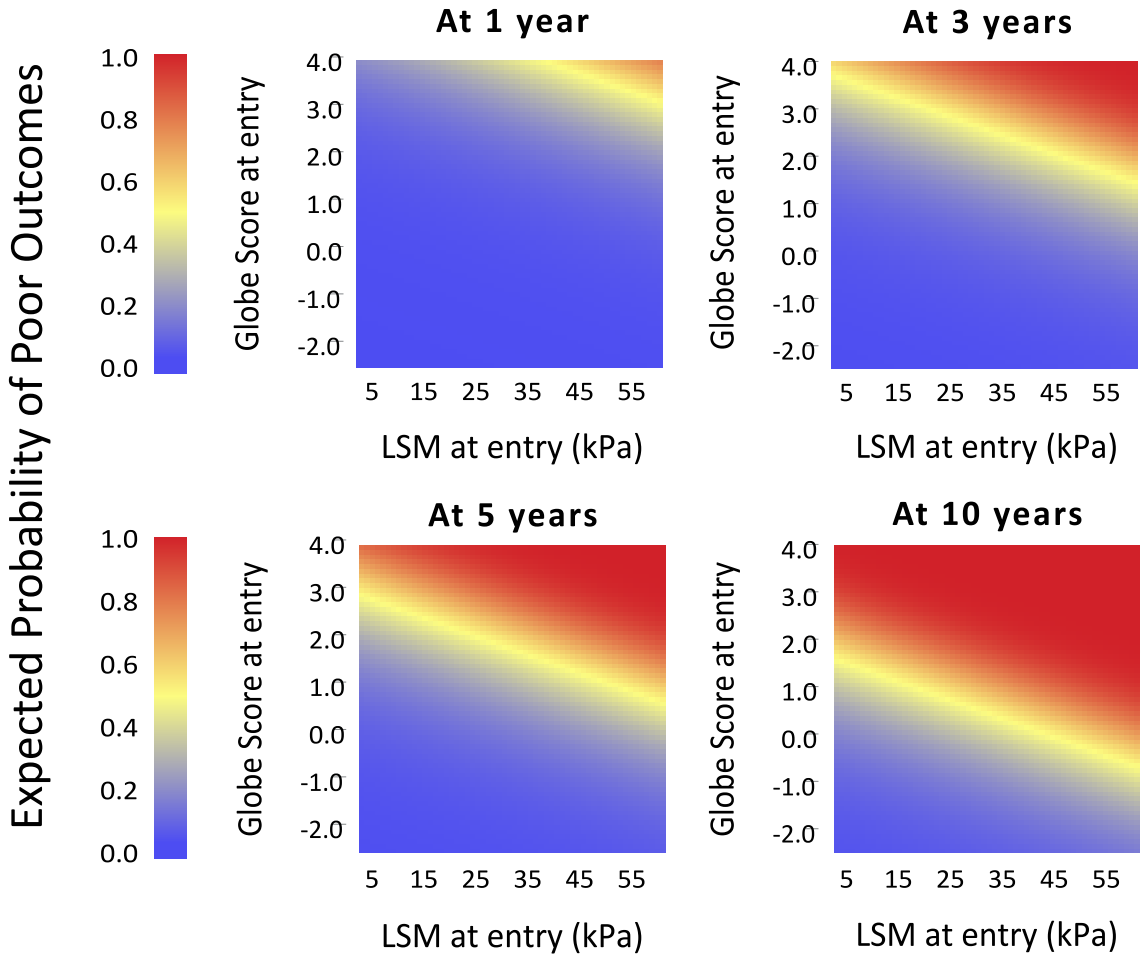
LSM by FibroScan®



+

Globe Score

Liver Complications, Transplantation, or Death



Probabilities and 95% confidence intervals are computable at: https://triton.iplesp.upmc.fr/webcalculator/

HIGHLIGHTS

- Although recommended by clinical practice guidelines for the assessment and monitoring of primary biliary cholangitis (PBC), liver stiffness measurement (LSM) by vibration-controlled transient elastography (VCTE) has not yet been validated as a relevant predictive marker of poor clinical outcome in this disease.
- In this large international study of LSM by VCTE in PBC (> 3,000 patients), LSM improved prediction of survival beyond established biochemical response criteria and prognostic scores and its prognostic value was externally validated.
- The thresholds of 8 kPa and 15 kPa optimally discriminated patients into low, medium, and high-risk groups. Forty percent of patients were at medium to high risk of poor clinical outcomes according to these thresholds.
- LSM by VCTE is a major, validated prognostic marker of PBC. Whether it can be used in trials as a surrogate endpoint for clinical benefit should be considered.