

Urinary Liver-Type Fatty Acid-Binding Protein and Progression of Diabetic Nephropathy in Type 1 Diabetes

NICOLAE M. PANDURU, MD, PHD^{1,2}
CAROL FORSBLOM, DMSC^{2,3}
MARKKU SARAHEIMO, MD, DMSC^{2,3}
LENA THORN, MD, DMSC^{2,3}
ANGELIKA BIERHAUS, PHD^{4†}

PER M. HUMPERT, PHD⁵
PER-HENRIK GROOP, MD, DMSC^{2,3,6}
ON BEHALF OF THE FINNDIANE STUDY
GROUP*

OBJECTIVE—Diabetic nephropathy (DN) has mainly been considered a glomerular disease, although tubular dysfunction may also play a role. This study assessed the predictive value for progression of a tubular marker, urinary liver-type fatty acid-binding protein (L-FABP), at all stages of DN.

RESEARCH DESIGN AND METHODS—At baseline, 1,549 patients with type 1 diabetes had an albumin excretion rate (AER) within normal reference ranges, 334 had microalbuminuria, and 363 had macroalbuminuria. Patients were monitored for a median of 5.8 years (95% CI 5.7–5.9). In addition, 208 nondiabetic subjects were studied. L-FABP was measured by ELISA and normalized with urinary creatinine. Different Cox proportional hazard models for the progression at every stage of DN were used to evaluate the predictive value of L-FABP. The potential benefit of using L-FABP alone or together with AER was assessed by receiver operating characteristic curve analyses.

RESULTS—L-FABP was an independent predictor of progression at all stages of DN. As would be expected, receiver operating characteristic curves for the prediction of progression were significantly larger for AER than for L-FABP, except for patients with baseline macroalbuminuria, in whom the areas were similar. Adding L-FABP to AER in the models did not significantly improve risk prediction of progression in favor of the combination of L-FABP plus AER compared with AER alone.

CONCLUSIONS—L-FABP is an independent predictor of progression of DN irrespective of disease stage. L-FABP used alone or together with AER may not improve the risk prediction of DN progression in patients with type 1 diabetes, but further studies are needed in this regard.

Diabetes Care 36:2077–2083, 2013

Diabetic nephropathy (DN) affects ~30% of all patients with type 1 diabetes. It is also the most severe diabetes complication because it is associated with progression to end-stage renal

disease (ESRD) and a high risk of premature death (1,2).

Early screening and detection is essential for the prevention of DN and is currently based on the measurement of

the urinary albumin excretion rate (AER) (3). An increased AER is regarded as a marker of glomerular injury, and its early diagnosis makes intervention possible before renal function starts to decline, as reflected by an impaired glomerular filtration rate (GFR). However, AER has some limitations, at both the early and the late stages of disease (4–6).

Although DN has long been considered a glomerular disease, tubulointerstitial injury has also been demonstrated to play a role in the pathogenesis (7). In this context, it is attractive to study molecules that are linked to tubular dysfunction. These molecules may serve as potential new markers for DN and may also provide additional information about clinical course or prognosis that may enable an earlier diagnosis and means to better tailor the treatment.

Urinary liver-type fatty acid-binding protein (L-FABP) is mainly regarded as a urinary tubular biomarker associated with structural and functional kidney damage (8). Urinary levels of L-FABP are not influenced by its serum levels because urinary L-FABP originates mainly from the tubular cells (9). This biomarker is elevated in the early stages of diabetes but is also influenced by lipid-lowering medication and angiotensin II receptor antagonists (10–12). Urinary L-FABP predicts adverse outcomes in acute kidney injury and progression of chronic kidney disease of nondiabetic causes (13–15). It is of note that urinary L-FABP has been linked to DN in patients with type 2 diabetes and has furthermore been suggested to be a predictor of progression to microalbuminuria in patients with type 1 diabetes (16,17). However, whether L-FABP would be a more sensitive marker of DN than AER or whether its predictive role is solely confined to the progression of the disease process is not yet known. Therefore, the aim of the current study is to investigate if baseline levels of L-FABP predict the development of DN and its progression at any stage of the disease and if the use of L-FABP alone or together with AER adds a benefit compared with current standard testing by AER.

From the ¹Second Clinical Department, “Carol Davila” University of Medicine and Pharmacy, Bucharest, Romania; the ²Folkhälsan Institute of Genetics, Folkhälsan Research Center, Helsinki, Finland; the ³Division of Nephrology, Department of Medicine, Helsinki University Central Hospital, Helsinki, Finland; the ⁴Department of Medicine 1 and Clinical Chemistry, University of Heidelberg, Heidelberg, Germany; ⁵Stoffwechselzentrum Rhein Pfalz, Mannheim, Germany; and the ⁶Baker IDI Heart and Diabetes Institute, Melbourne, Victoria, Australia.

Corresponding author: Per-Henrik Groop, per-henrik.groop@helsinki.fi.

Received 12 September 2012 and accepted 2 January 2013.

DOI: 10.2337/dc12-1868

This article contains Supplementary Data online at <http://care.diabetesjournals.org/lookup/suppl/doi:10.2337/dc12-1868/-/DC1>.

P.M.H. and P.-H.G. contributed equally to this work.

†Deceased.

*A complete list of physicians and nurses is presented in the Supplementary Data online.

© 2013 by the American Diabetes Association. Readers may use this article as long as the work is properly cited, the use is educational and not for profit, and the work is not altered. See <http://creativecommons.org/licenses/by-nc-nd/3.0/> for details.

RESEARCH DESIGN AND METHODS

Study sample

This study is part of the ongoing Finnish Diabetic Nephropathy Study (Finn-Diane). The study protocol has been described elsewhere and approved by the local ethics committees of all participating centers (18). Written informed consent was obtained from each patient, and the study was performed in accordance with the Declaration of Helsinki.

Blood and urine samples for the current study were collected at baseline for patients who were enrolled between January 1998 and December 2002 and stored at -20°C until 2008. Patients were monitored for a median of 5.8 years (95% CI 5.7–5.9), and clinical outcomes were ascertained. After patients with ESRD were excluded, 1,886 patients remained in the study. The control group comprised nondiabetic subjects without a first- or second-degree relative with kidney disease or diabetes.

Cohort characteristics

Baseline data on medication and diabetes complications were registered with the use of a standardized questionnaire, which was completed by the attending physician using information from the medical files.

Blood pressure, height, weight, and waist-to-hip ratio (WHR) were assessed. Blood was drawn for measurement of HbA_{1c} , lipids, and cystatin C. Assessment of biochemical variables has been described elsewhere (19).

Urinary L-FABP was quantified, in a single 24-h urine collection, using a research L-FABP Elecsys assay on the Cobas Elecsys 411 Immunoanalyzer (Roche Diagnostics GmbH, Mannheim, Germany). To determine L-FABP in urine, human urine samples were automatically treated with an alkaline pretreatment that causes the denaturation of proteins in the sample. A biotinylated monoclonal antibody (capture antibody), combined with a ruthenium-labeled monoclonal antibody (detection antibody), reacted with the antigen to form a sandwich complex. After addition of streptavidin-coated beads, this complex became bound to the beads via interaction of biotin and streptavidin.

This mixture was aspirated into the measuring cell, where the beads were magnetically captured onto the surface of the electrode. Emission of photons

derived from chemiluminescent reaction was measured by a photomultiplier. The assay demonstrated repeatability below 7% coefficient of variation and a recovery in serial measurements of $\sim 100 \pm 10\%$. The lower detection limit of the assay was determined ($<0.1 \text{ ng/mL}$), and no cross-reactivity was observed for the other FABP types. For evaluation, the resulting urinary L-FABP values were normalized with urinary creatinine.

Renal status was defined based on the AER in at least two of three timed urine collections. Patients were divided by AER categorically into those with normal AER ($<30 \text{ mg/24 h}$ or $<20 \mu\text{g/min}$), microalbuminuria ($30\text{--}300 \text{ mg/24 h}$ or $20\text{--}200 \mu\text{g/min}$), and macroalbuminuria ($>300 \text{ mg/24 h}$ or $>200 \mu\text{g/min}$). Presence of ESRD was defined according to whether patients were undergoing dialysis or had received a kidney transplant (patients with ESRD were excluded at baseline). The GFR was estimated with a formula based on cystatin C (20).

During follow-up, all patients were managed by their own practitioner and diabetes team, without any attempt to standardize care.

Ascertainment of outcomes

Progression of DN was defined as the passage from one stage to the next based on AER thresholds. ESRD was defined as the requirement of dialysis or kidney transplantation and was identified via a search of the renal registries or center databases and verified from medical files.

Statistical analysis

Normally distributed variables are presented as mean \pm SD. Variables nonnormally distributed are presented as median and interquartile range. Comparison between the groups was performed by one-way ANOVA for normally distributed variables and by Mann-Whitney U test for nonparametric distributions. Categorical variables were compared between the groups using the χ^2 test.

Cox proportional hazards models were used to analyze the values of L-FABP as an explanatory variable for progression of DN. Separate Cox proportional hazards models were constructed to predict progression at the various stages of DN. The basic models of progression were built by starting with all known risk factors for DN. All of the single covariates were first tested in univariate analysis, and only the significant ones were selected for further analysis. The sets of

significant covariates from the univariate analysis were tested in the Cox regression proportional hazards models by using a backward selection algorithm. The variables retained in the models after backward selection constituted the final basic models. Then L-FABP or AER were included in these basic models. Finally, both L-FABP and AER were included in the models. We tested for interaction between variables included in the basic model, but no significant interaction was detected.

The models were also compared using time-dependent receiver operating characteristic (ROC) curve analysis to assess the clinical benefit of using L-FABP, alone or on top of the current clinical standard (AER), as a predictor of DN progression at any stage of the disease.

To see if treatment influenced the results, we performed a supplementary analysis adjusting the models for medications that have been shown to influence urinary L-FABP and AER concentration, including ACE inhibitors, angiotensin II receptor blockers, and any antihypertensive medication, as well as lipid-lowering treatment (21). P values < 0.05 were considered statistically significant. The data analysis was performed using MedCalc 12.1.3.0 software (MedCalc Software BVBA, Mariakerke, Belgium) and SPSS 19.0 software (IBM Corporation, Armonk, NY).

RESULTS

Cohort characteristics

Baseline characteristics (Table 1) were used to divide the 2,454 patients with type 1 diabetes into three groups: 1,549 with normal AER, 334 with microalbuminuria, and 363 with macroalbuminuria. In addition, 208 nondiabetic subjects served as the control group. Patients were monitored for 5.8 years (95% CI 5.7–5.9). During the follow-up period, 112 patients with type 1 diabetes progressed from normal AER to microalbuminuria, 46 progressed from microalbuminuria to macroalbuminuria, and 78 progressed from macroalbuminuria to ESRD. The clinical baseline characteristics of progressors and nonprogressors, for all stages of DN, are described in Supplementary Table 1. Progressors from normal AER to microalbuminuria had higher BMI, systolic blood pressure, diastolic blood pressure, HbA_{1c} , total cholesterol, LDL cholesterol, triglycerides, and AER. Patients who progressed from

Table 1—Clinical baseline data for subjects enrolled in the study

Variable	Healthy control subjects <i>n</i> = 208	Patient groups		
		Normoalbuminuric <i>n</i> = 1,549	Microalbuminuric <i>n</i> = 334	Macroalbuminuric <i>n</i> = 363
Sex				
Males	106	732	195	199
Females	102	817	139	164
Age (years)	35.9 ± 11.3	36.2 ± 12.3	38.8 ± 12.7	41.8 ± 10.5
Age of onset (years)	—	17.4 ± 9.3	13.0 ± 9.1	12.5 ± 8.5
Duration (years)	—	18.8 ± 11.7	25.7 ± 11.1	29.3 ± 8.1
BMI (kg/m ²)	24.0 ± 3.0	24.9 ± 3.5	25.6 ± 3.6	26.2 ± 4.1
WHR				
Males	0.92 ± 0.06	0.89 ± 0.07	0.92 ± 0.07	0.94 ± 0.07
Females	0.83 ± 0.05	0.80 ± 0.06	0.83 ± 0.07	0.84 ± 0.07
Smoking history (%)	22.3	41.2	52.4	60.4
Blood pressure (mmHg)				
Systolic	126 ± 15	130 ± 16	136 ± 17	143 ± 20
Diastolic	77 ± 9	78 ± 9	81 ± 10	83 ± 10
HbA _{1c} (%)	5.5 ± 0.4	8.2 ± 1.4	8.8 ± 1.5	9.0 ± 1.6
Cholesterol (mmol/L)				
Total	4.75 ± 0.88	4.80 ± 0.90	4.97 ± 0.88	5.39 ± 1.09
HDL	1.55 ± 0.33	1.35 ± 0.37	1.30 ± 0.39	1.21 ± 0.37
LDL	2.76 ± 0.82	2.95 ± 0.81	3.08 ± 0.80	3.39 ± 0.89
Triglycerides (mmol/L)	0.90 (0.84–0.97)	0.94 (0.92–0.97)	1.08 (1.02–1.14)	1.36 (1.27–1.46)
AER (mg/24 h)	3 (2–3)	8 (7–8)	50 (43–58)	453 (371–584)
eGFR (mL/min/1.73 m ²)	111 ± 36	101 ± 24	90 ± 24	60 ± 40
L-FABP (μg/μmol)	0.014 (0.008–0.020)	0.039 (0.036–0.044)	0.091 (0.074–0.107)	0.504 (0.426–0.643)

Categorical data are presented as numbers, and continuous data are presented as mean ± SD, median (interquartile range), or percentage.

microalbuminuria to macroalbuminuria more often had a history of smoking and higher WHR, diastolic blood pressure, HbA_{1c}, total cholesterol, triglycerides, and AER. Patients who progressed from macroalbuminuria to ESRD had higher systolic blood pressure, total cholesterol, triglycerides, and AER and lower estimated GFR (eGFR).

Levels of L-FABP were significantly higher ($P < 0.001$) in patients with type 1 diabetes and normal AER (0.075 μg/μmol) than in nondiabetic subjects (0.014 μg/μmol). Urinary L-FABP levels increased in parallel with worsening stage of DN (Fig. 1A). L-FABP was higher in the progressors than in nonprogressors at any stage of DN (Fig. 1B).

Progression from normal AER to microalbuminuria

Univariate analysis showed L-FABP predicted the progression from normal AER to microalbuminuria with a hazard ratio (HR) of 4.10 (95% CI 2.31–7.27; $P < 0.001$). To analyze this association in more detail, we used a backward selection procedure to create a Cox regression model out of all of the other potential

risk factors as described in RESEARCH DESIGN AND METHODS. The variables that remained in the basic model were: WHR, history of smoking, HbA_{1c}, and total cholesterol. When we included L-FABP in this Cox regression model, L-FABP remained significant (3.22 [1.74–5.95], $P < 0.001$). Finally, when we added AER to the model, L-FABP still remained an independent predictor of progression to microalbuminuria (2.97 [1.49–5.89], $P = 0.002$). AER as a single variable was then added alone to the basic model and together with L-FABP predicted progression to microalbuminuria in all three analyses (Table 2).

When we assessed the potential benefit of using L-FABP instead of AER for the prediction of progression with ROC curve analyses adjusted for the basic model, we found that the area under the curve (AUC [95% CI]) for L-FABP (AUC_{L-FABP}) was smaller than the AUC for AER (AUC_{AER}) at 0.735 (0.711–0.757) vs. 0.778 (0.756–0.799; $P < 0.001$), suggesting that AER performs better. When both urinary biomarkers were included in the model, the AUC of L-FABP plus AER (AUC_{L-FABP&AER}) was 0.786 (0.765–0.807), which was not

significantly larger (Δ AUCs 0.008, $P = 0.09$) then the AUC_{AER} (0.778 [0.756–0.799]) in patients with type 1 diabetes and normal AER (Fig. 2; Supplementary Table 2).

Progression from microalbuminuria to macroalbuminuria

In microalbuminuric patients, univariate analysis (HR [95% CI]) showed that L-FABP is a predictor of progression to macroalbuminuria (1.49 [1.20–1.85], $P < 0.001$). To show that L-FABP is independent from other risk factors, a basic model of progression to macroalbuminuria was built and comprised WHR, HbA_{1c}, and triglycerides. L-FABP remained an independent predictor of progression to macroalbuminuria (1.40 [1.10–1.79], $P = 0.006$) when it was added to the basic model. We also wanted to see if L-FABP is independent of AER and added AER to the previous model. Even in this model, L-FABP was an independent predictor of progression to macroalbuminuria (0.673 [0.476–0.954], $P = 0.026$). As expected, AER predicted the progression to macroalbuminuria in all models (Table 2).

We used ROC analysis to assess the potential benefit of using L-FABP instead

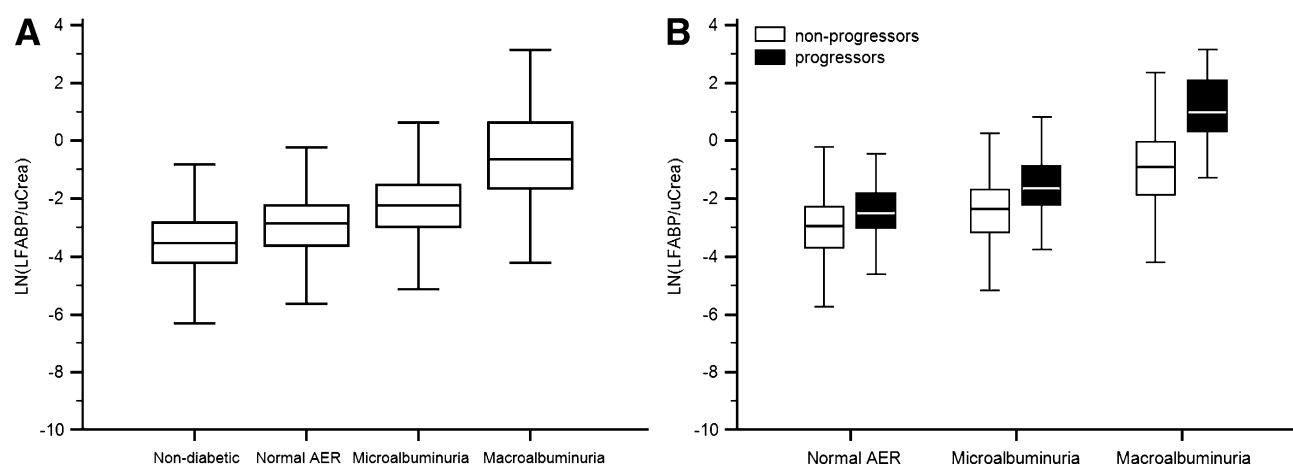


Figure 1—A: Urinary L-FABP levels across study groups at baseline. The L-FABP levels were significantly different among the study groups. Significant differences ($P < 0.001$) in L-FABP levels were observed between the macroalbuminuria group and all other groups. L-FABP levels in the microalbuminuria group were significantly different ($P < 0.001$) from healthy patients and those with type 1 diabetes and normal AER. Patients with type 1 diabetes and normal AER had significantly ($P < 0.001$) higher L-FABP levels than healthy patients. B: Urinary L-FABP levels across study groups at baseline in relation with progression status. L-FABP level is significantly higher ($P < 0.001$) for progressors across all groups (normal AER, microalbuminuria, and macroalbuminuria) compared with nonprogressors. The horizontal line in the middle of each box indicates the median; the top and bottom borders of the box mark the 75th and 25th percentiles, respectively, and the whiskers mark the 90th and 10th percentiles.

of AER. When we compared the AUCs of each marker used on top of the basic progression model, AUC_{AER} was slightly larger than AUC_{L-FABP} (0.847 [95% CI 0.803–0.898] vs. 0.777 [0.728–0.821], $P = 0.034$), suggesting that AER is a better predictor of progression to macroalbuminuria. When we analyzed whether the concomitant use of both biomarkers added benefit compared with AER alone, we found that there was no difference between $AUC_{AER \& L-FABP}$ and AUC_{AER} ($P = 0.40$; Fig. 2; Supplementary Table 2).

Progression to ESRD in macroalbuminuric patients

Unadjusted L-FABP predicted the progression to ESRD (HR 1.24 [95% CI 1.19–1.28],

$P < 0.001$) in univariate Cox regression analysis. The basic model of progression to ESRD included eGFR and triglycerides. When we added L-FABP to this model, it was independent of the other covariates (1.20 [1.14–1.25], $P < 0.001$). When we further adjusted the model for AER, L-FABP remained an independent predictor of progression to ESRD (1.16 [1.10–1.23], $P = 0.023$; Table 2).

ROC curve analysis revealed that there was no difference between AUC_{AER} and AUC_{L-FABP} ($\Delta AUC_s = 0.011$, $P = 0.280$). Also, when we compared the use of L-FABP together with AER for the prediction of progression to ESRD, the difference between $AUC_{L-FABP \& AER}$ and

AUC_{AER} was nonsignificant ($\Delta AUC_s = 0.002$, $P = 0.819$; Fig. 2; Supplementary Table 2).

Effect of treatment on prediction of progression

When we adjusted the L-FABP findings for the use of medication, the results were still significant for all tested medication (data not shown), except for ACE inhibitors (HR 0.773 [95% CI 0.540–1.107], $P = 0.161$) or any antihypertensive medication (0.759 [0.524–1.100], $P = 0.147$), at the stage of microalbuminuria.

CONCLUSIONS—To our knowledge, this is the first study in type 1 diabetes to show that L-FABP is an independent

Table 2—Prediction of progression using Cox regression analysis with baseline data for L-FABP and AER

	Unadjusted (univariate)		Adjusted for basic model		Adjusted for basic model and AER	
	HR (95% CI)	P value	HR (95% CI)	P value	HR (95% CI)	P value
Normoalbuminuria						
AER (mg/24 h)	1.0159 (1.0131–1.0187)	<0.0001	1.0155 (1.0120–1.0189)	<0.0001	1.0149 (1.0115–1.0184)	<0.0001
L-FABP ($\mu\text{g}/\mu\text{mol}$)	4.1006 (2.3103–7.2783)	<0.0001	3.2215 (1.7413–5.9597)	0.0002	2.9706 (1.4961–5.8982)	0.0020
Microalbuminuria						
AER (mg/24 h)	1.0061 (1.0048–1.0074)	<0.0001	1.0075 (1.0053–1.0097)	<0.0001	1.0113 (1.0074–1.0152)	<0.0001
L-FABP ($\mu\text{g}/\mu\text{mol}$)	1.4912 (1.2008–1.8517)	0.0003	1.4061 (1.1029–1.7926)	0.0062	0.6733 (0.4756–0.9533)	0.0265
Macroalbuminuria						
AER (mg/24 h)	1.0005 (1.0004–1.0005)	<0.0001	1.0003 (1.0002–1.0004)	<0.0001	1.0001 (1.0000–1.0003)	0.0225
L-FABP ($\mu\text{g}/\mu\text{mol}$)	1.2410 (1.1963–1.2874)	<0.0001	1.2001 (1.1442–1.2586)	<0.0001	1.1686 (1.1045–1.2365)	<0.0001

Basic models for progression for every stage are described in RESEARCH DESIGN AND METHODS.

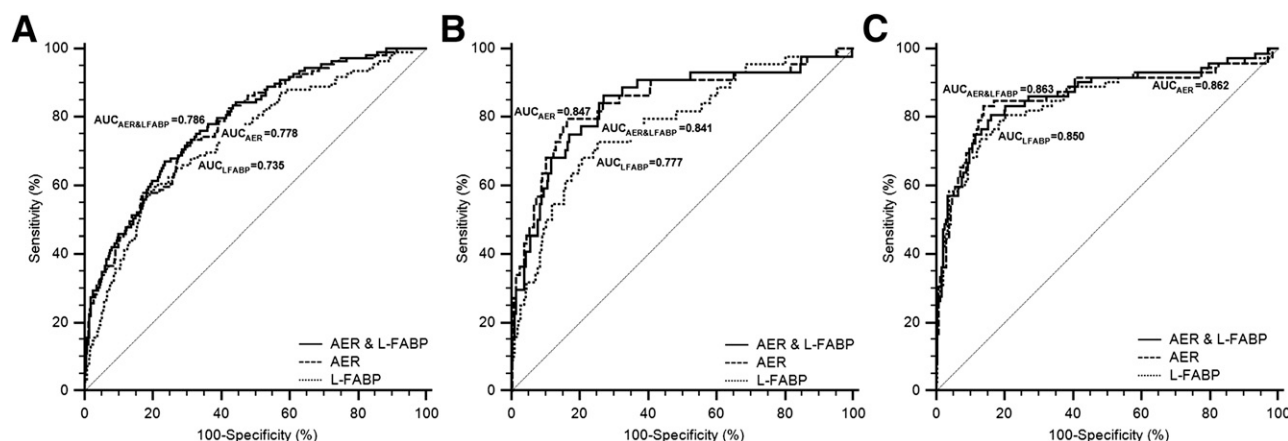


Figure 2—A: ROC curve analysis for L-FABP and AER in patients with type 1 diabetes and normal AER showed a trend toward an improvement of the risk prediction ($P = 0.09$) for L-FABP used together with AER ($AUC_{L-FABP \& AER} = 0.786$) compared with AER used alone ($AUC_{AER} = 0.778$) in patients with type 1 diabetes and normal AER. B: ROC curve analysis for L-FABP and AER in the microalbuminuria group found no significant difference between AUC_{AER} (0.847) and $AUC_{L-FABP \& AER}$ (0.841). AUC_{L-FABP} (0.777) was significantly smaller than AUC_{AER} ($P = 0.034$). C: ROC curve analysis for L-FABP and AER in the macroalbuminuria group found no significant difference between AUC_{AER} (0.862) and $AUC_{L-FABP \& AER}$ (0.863). $AUC_{AER \& L-FABP}$ was significantly larger ($P = 0.012$) than AUC_{L-FABP} (0.850).

predictor of progression across all stages of DN. Another interesting finding of this study is that the use of L-FABP together with AER may not improve the risk prediction of DN progression in patients with type 1 diabetes.

The finding that L-FABP is a predictor of progression in patients with type 1 diabetes and normal AER has been suggested earlier, but that study did not have the power to show a predictive value of L-FABP as a continuous variable (17). Our study demonstrates the predictive value of L-FABP not only in patients with type 1 diabetes and normal AER but also across all stages of DN. This may represent an important result, because L-FABP is closely associated with structural and functional tubular kidney damage, and for patients with AER in the “normal” range, we still have no other biomarker or algorithm to identify those at risk for progression to microalbuminuria (10,22).

The ROC curve analysis, however, did not show any benefit of using L-FABP to predict progression to a higher stage, most likely because the progression of DN from microalbuminuria to macroalbuminuria in this study was defined by change in AER. Using an AER definition of progression makes it very difficult for any other variable to outperform the gold standard, the AER. Although recent studies have challenged the classification based on AER, the AER is still useful at the early stages before any decline in GFR occurs and mirrors the progression of more than 70% of patients with DN

(6,23). Another option to define progression could be based on change in GFR. This may better reflect the final outcomes compared with AER but might not give enough information at the early stages of DN. This approach was used to define progression to ESRD, but AER was still a better predictor of progression in this late stage of DN.

Another result of our study is that in the microalbuminuria group, before the adjustment with AER, L-FABP was an independent predictor of progression to macroalbuminuria (HR 1.40 [95% CI 1.10–1.79], $P = 0.006$), and after adjustment for AER, there was surprisingly a protective HR of 0.67 (0.47–0.95, $P = 0.02$). This result may be a consequence of lower statistical power in this group (46 progressors) or a stronger correlation between AER and L-FABP ($r = 0.49$) in patients with microalbuminuria, although these alternatives would not explain why L-FABP was an independent predictor in the first place. Another possible explanation could be an effect of medication, because L-FABP was no longer significant in the microalbuminuria group after adjustment for ACE inhibitors or any antihypertensive medication. This is no surprise, because treatment with ACE inhibitors strongly reduces the AER and/or L-FABP levels and influences progression of DN. The lower HR may also be the consequence of a possible protective role of L-FABP against tubulointerstitial damage aggravated by elevated AER, but we cannot prove this possible hypothesis (24).

Our results regarding prediction of DN progression are due to the continuous increase in the L-FABP levels alongside the worsening of the nephropathy stage (10,16). The pathophysiological role of this continuous increase is not completely known but may mirror different mechanisms across DN stages. In early diabetes, before the onset of microalbuminuria, mild hyperglycemia and activation of the intrarenal renin-angiotensin-aldosterone system (RAAS) may lead to oxidative stress at the postglomerular capillary level (25,26). This in turn decreases the availability of NO, which, together with RAAS activation and functional denervation, may lead to vasoconstriction and hypoxia in the tubular cells (27,28). Chronic hypoxia might then trigger L-FABP gene overexpression and an increased urinary excretion of L-FABP (29). That an early increase in L-FABP might be independent of AER is further supported by the poor correlation between the two variables ($r = 0.15$) in the normoalbuminuric patients as well as the independent predictive value of L-FABP for the progression from normal AER to microalbuminuria. In addition, L-FABP increase seems to be connected with tubular injury rather than diabetes itself because L-FABP was poorly correlated with HbA_{1c} ($r = 0.06$ in nondiabetic subjects; $r = 0.11$ in patients with type 1 diabetes and normal AER). Once microalbuminuria appears, binding of fatty acids to albumin may trigger fatty acid overload in the proximal tubules, and the L-FABP gene may, as a consequence, be upregulated to increase

the free fatty acid transport into the mitochondria. The urinary excretion of L-FABP may then increase again, but such a mechanism has still been considered controversial (8,30,31). At the late stages, oxidative stress and hypoxia (accentuated by anemia) probably cooperate with the elevated AER and cause an L-FABP elevation (28).

The strengths of this study are the large number of patients, long follow-up data of patients, and thorough phenotypic characterization. One potential limitation of the study is that we have no data regarding anemia. Anemia may already be present at the early stages of DN and can potentially increase urinary L-FABP if it is severe enough (32,33). However, at least severe anemia was not an issue in this study because none of the patients received erythropoietin or other treatment for anemia.

In summary, this study shows that L-FABP is an independent predictor of DN progression, irrespective of the disease stage. L-FABP used alone or together with AER may not improve the risk prediction of DN progression in patients with type 1 diabetes, but further studies are needed in this regard.

Acknowledgments—The study was supported by grants from the Folkhälsan Research Foundation, the Wilhelm and Else Stockmann Foundation, the Liv och Hälsa Foundation, and the Finnish Medical Society (Finska Läkaresällskapet).

N.M.P. was supported by the Sectoral Operational Programme—Human Resources Development (SOP-HRD), financed from the European Social Fund, and by the Romanian Government under the contract number POSDRU/89/1.5/S/64109. M.S. is an advisory board member for Medtronic in Scandinavia and has received lecture fees from Eli Lilly, Medtronic Finland, Novartis, Novo Nordisk, Roche, Sanofi, and MSD. P.-H.G. has received research grants from Eli Lilly and Roche; is an advisory board member for Boehringer Ingelheim, Novartis, Cebix, and Abbott; and has received lecture fees from Boehringer Ingelheim, Eli Lilly, Genzyme, Novartis, Novo Nordisk, Sanofi, and MSD. Analyses and assays for urinary L-FABP were partly sponsored by Roche Diagnostics; however, the sponsors were not involved in the conduct of the study. No other potential conflicts of interest relevant to this article were reported.

N.M.P. researched data, performed statistical analyses, and wrote the manuscript. C.F., M.S., L.T., and A.B. researched data, contributed to discussion, and reviewed and edited the manuscript. P.M.H., and P.-H.G. contributed to discussion and reviewed and edited the

manuscript. P.-H.G. is the guarantor of this study and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Parts of this study were presented in abstract form at the 48th European Association for the Study of Diabetes Congress, Berlin, Germany, 1–6 October 2012.

The authors thank the skilled laboratory technicians Maikki Parkkonen, Anna-Reetta Salonen, Anna Sandelin, Tuula Soppela, and Jaana Tuomikangas (Folkhälsan Institute of Genetics, Folkhälsan Research Center, Helsinki, Finland) and Renate Sedlmaier-Prasselsperger and Kerstin Jaensch (Roche, Germany) for the excellent organization and measurements of urine samples on the Elecsys system. Finally, the authors acknowledge the physicians and nurses at each center participating in the collection of patients.

References

1. Groop PH, Thomas MC, Moran JL, et al.; FinnDiane Study Group. The presence and severity of chronic kidney disease predicts all-cause mortality in type 1 diabetes. *Diabetes* 2009;58:1651–1658
2. Forsblom C, Harjutsalo V, Thorn LM, et al.; FinnDiane Study Group. Competing-risk analysis of ESRD and death among patients with type 1 diabetes and macroalbuminuria. *J Am Soc Nephrol* 2011;22:537–544
3. Viberti GC, Hill RD, Jarrett RJ, Argyropoulos A, Mahmud U, Keen H. Microalbuminuria as a predictor of clinical nephropathy in insulin-dependent diabetes mellitus. *Lancet* 1982;1:1430–1432
4. Fioretto P, Steffes MW, Mauer M. Glomerular structure in nonproteinuric IDDM patients with various levels of albuminuria. *Diabetes* 1994;43:1358–1364
5. Forsblom CM, Groop PH, Ekstrand A, Groop LC. Predictive value of microalbuminuria in patients with insulin-dependent diabetes of long duration. *BMJ* 1992;305:1051–1053
6. Molitch ME, Steffes M, Sun W, et al.; Epidemiology of Diabetes Interventions and Complications Study Group. Development and progression of renal insufficiency with and without albuminuria in adults with type 1 diabetes in the diabetes control and complications trial and the epidemiology of diabetes interventions and complications study. *Diabetes Care* 2010;33:1536–1543
7. Magri CJ, Fava S. The role of tubular injury in diabetic nephropathy. *Eur J Intern Med* 2009;20:551–555
8. Kamijo A, Sugaya T, Hikawa A, et al. Urinary excretion of fatty acid-binding protein reflects stress overload on the proximal tubules. *Am J Pathol* 2004;165:1243–1255
9. Kamijo A, Sugaya T, Hikawa A, et al. Urinary liver-type fatty acid binding protein as a useful biomarker in chronic kidney disease. *Mol Cell Biochem* 2006;284:175–182
10. Nielsen SE, Sugaya T, Tarnow L, et al. Tubular and glomerular injury in diabetes and the impact of ACE inhibition. *Diabetes Care* 2009;32:1684–1688
11. Nakamura T, Sugaya T, Kawagoe Y, Ueda Y, Osada S, Koide H. Effect of pitavastatin on urinary liver-type fatty acid-binding protein levels in patients with early diabetic nephropathy. *Diabetes Care* 2005;28:2728–2732
12. Nakamura T, Sugaya T, Koide H. Angiotensin II receptor antagonist reduces urinary liver-type fatty acid-binding protein levels in patients with diabetic nephropathy and chronic renal failure. *Diabetologia* 2007;50:490–492
13. Ferguson MA, Vaidya VS, Waikar SS, et al. Urinary liver-type fatty acid-binding protein predicts adverse outcomes in acute kidney injury. *Kidney Int* 2010;77:708–714
14. Mou S, Wang Q, Li J, Shi B, Ni Z. Urinary excretion of liver-type fatty acid-binding protein as a marker of progressive kidney function deterioration in patients with chronic glomerulonephritis. *Clin Chim Acta* 2012;413:187–191
15. Nakamura T, Sugaya T, Ebihara I, Koide H. Urinary liver-type fatty acid-binding protein: discrimination between IgA nephropathy and thin basement membrane nephropathy. *Am J Nephrol* 2005;25:447–450
16. Kamijo-Ikemori A, Sugaya T, Yasuda T, et al. Clinical significance of urinary liver-type fatty acid-binding protein in diabetic nephropathy of type 2 diabetic patients. *Diabetes Care* 2011;34:691–696
17. Nielsen SE, Sugaya T, Hovind P, Baba T, Parving HH, Rossing P. Urinary liver-type fatty acid-binding protein predicts progression to nephropathy in type 1 diabetic patients. *Diabetes Care* 2010;33:1320–1324
18. Thorn LM, Forsblom C, Fagerudd J, et al.; FinnDiane Study Group. Metabolic syndrome in type 1 diabetes: association with diabetic nephropathy and glycemic control (the FinnDiane study). *Diabetes Care* 2005;28:2019–2024
19. Thorn LM, Forsblom C, Wadén J, et al.; Finnish Diabetic Nephropathy (FinnDiane) Study Group. Metabolic syndrome as a risk factor for cardiovascular disease, mortality, and progression of diabetic nephropathy in type 1 diabetes. *Diabetes Care* 2009;32:950–952
20. Stevens LA, Coresh J, Schmid CH, et al. Estimating GFR using serum cystatin C alone and in combination with serum creatinine: a pooled analysis of 3,418 individuals with CKD. *Am J Kidney Dis* 2008;51:395–406
21. Nakamura T, Sugaya T, Kawagoe Y, et al. Azelnidipine reduces urinary protein

- excretion and urinary liver-type fatty acid binding protein in patients with hypertensive chronic kidney disease. *Am J Med Sci* 2007;333:321–326
22. Maatman RG, van de Westerlo EM, van Kuppevelt TH, Veerkamp JH. Molecular identification of the liver- and the heart-type fatty acid-binding proteins in human and rat kidney. Use of the reverse transcriptase polymerase chain reaction. *Biochem J* 1992;288:285–290
 23. Costacou T, Ellis D, Fried L, Orchard TJ. Sequence of progression of albuminuria and decreased GFR in persons with type 1 diabetes: a cohort study. *Am J Kidney Dis* 2007;50:721–732
 24. Kamijo A, Kimura K, Sugaya T, et al. Urinary free fatty acids bound to albumin aggravate tubulointerstitial damage. *Kidney Int* 2002;62:1628–1637
 25. Yaqoob M, McClelland P, Patrick AW, et al. Evidence of oxidant injury and tubular damage in early diabetic nephropathy. *QJM* 1994;87:601–607
 26. Liu F, Brezniceanu ML, Wei CC, et al. Overexpression of angiotensinogen increases tubular apoptosis in diabetes. *J Am Soc Nephrol* 2008;19:269–280
 27. Yaqoob M, Patrick AW, McClelland P, et al. Relationship between markers of endothelial dysfunction, oxidant injury and tubular damage in patients with insulin-dependent diabetes mellitus. *Clin Sci (Lond)* 1993;85:557–562
 28. Singh DK, Winocour P, Farrington K. Mechanisms of disease: the hypoxic tubular hypothesis of diabetic nephropathy. *Nat Clin Pract Nephrol* 2008;4:216–226
 29. Yamamoto T, Noiri E, Ono Y, et al. Renal L-type fatty acid—binding protein in acute ischemic injury. *J Am Soc Nephrol* 2007;18:2894–2902
 30. Thomas ME, Schreiner GF. Contribution of proteinuria to progressive renal injury: consequences of tubular uptake of fatty acid bearing albumin. *Am J Nephrol* 1993;13:385–398
 31. Sasaki H, Kamijo-Ikemori A, Sugaya T, et al. Urinary fatty acids and liver-type fatty acid binding protein in diabetic nephropathy. *Nephron Clin Pract* 2009;112:c148–c156
 32. Al-Khoury S, Afzali B, Shah N, Covic A, Thomas S, Goldsmith DJ. Anaemia in diabetic patients with chronic kidney disease—prevalence and predictors. *Diabetologia* 2006;49:1183–1189
 33. von Eynatten M, Baumann M, Heemann U, et al. Urinary L-FABP and anaemia: distinct roles of urinary markers in type 2 diabetes. *Eur J Clin Invest* 2010;40:95–102