

The Association between Serum Uric Acid and the Incidence of Prediabetes and Type 2 Diabetes Mellitus: the Rotterdam Study

N. van der Schaft, A. Brahimaj, K.X. Wen, O.H. Franco, A. Dehghan

PloS One, 2017

ABSTRACT

Background

Limited evidence is available about the association between serum uric acid and sub-stages of the spectrum from normoglycemia to type 2 diabetes. We aimed to investigate the association between serum uric acid and risk of prediabetes and type 2 diabetes.

Methods

Eligible participants of the Rotterdam Study ($n = 8,367$) were classified into mutually exclusive subgroups of normoglycemia ($n = 7,030$) and prediabetes ($n = 1,337$) at baseline. These subgroups were followed up for incident prediabetes ($n = 1,071$) and incident type 2 diabetes ($n = 407$), respectively. We used Cox proportional hazard models to determine hazard ratios (HRs) for incident prediabetes among individuals with normoglycemia and incident type 2 diabetes among individuals with prediabetes.

Results

The mean duration of follow-up was 7.5 years for incident prediabetes and 7.2 years for incident type 2 diabetes. A standard deviation increment in serum uric acid was significantly associated with incident prediabetes among individuals with normoglycemia (HR 1.10, 95% confidence interval (CI) 1.01; 1.18), but not with incident type 2 diabetes among individuals with prediabetes (HR 1.07, 95% CI 0.94; 1.21). Exclusion of individuals who used diuretics or individuals with hypertension did not change our results. Serum uric acid was significantly associated with incident prediabetes among normoglycemic women (HR 1.13, 95% CI 1.02; 1.25) but not among normoglycemic men (HR 1.08, 95% CI 0.96; 1.21). In contrast, serum uric acid was significantly associated with incident type 2 diabetes among prediabetic men (HR 1.23, 95% CI 1.01; 1.48) but not among prediabetic women (HR 1.00, 95% CI 0.84; 1.19).

Conclusions

Our findings agree with the notion that serum uric acid is more closely related to early-phase mechanisms in the development of type 2 diabetes than late-phase mechanisms.

INTRODUCTION

Uric acid is generated during nucleotide and adenosine triphosphate (ATP) metabolism and comprises the end product of human purine metabolism.¹ We have previously demonstrated in a large population-based cohort study that elevated serum levels of uric acid are associated with increased risk of type 2 diabetes independently of other risk factors.² This association has since then been replicated in many other prospective studies and subsequent meta-analyses.³⁻⁶ In addition, serum uric acid has been associated with various cardiovascular and metabolic conditions such as hypertension, obesity, heart failure and atrial fibrillation in large population-based studies.⁷

Prediabetes is a disorder of glucose homeostasis characterized by impaired glucose tolerance or impaired fasting glucose. These are both reversible stages of intermediate hyperglycemia that provide an increased risk of type 2 diabetes.⁸ Prediabetes can therefore be regarded as an important reversible stage that could lead to type 2 diabetes, and early identification of prediabetes might contribute to the prevention of type 2 diabetes. Despite its established association with incident type 2 diabetes, serum uric acid has not been studied extensively in relation to incident prediabetes in individuals with normoglycemia or incident type 2 diabetes in individuals with established prediabetes.

Therefore, the objective of the present study is to determine whether serum uric acid is associated with incident prediabetes among normoglycemic individuals and type 2 diabetes among prediabetic individuals. This study is performed within the framework of the Rotterdam Study, a large population-based prospective cohort study of participants aged 45 years and older.⁹

MATERIALS AND METHODS

The Rotterdam Study

The methodology of the Rotterdam Study has been outlined extensively elsewhere.⁹ Briefly, the study initially consisted of 7,983 residents of the Ommoord district aged 55 years and over in the city of Rotterdam, the Netherlands (RS-I). Following extension of the cohort in 2000 (RS-II), when individuals who had become 55 years of age or moved into the district since the study start were added to the cohort, and 2006 (RS-III), when individuals aged 45-54 years also became eligible for participation, the total number of subjects was 14,926 by the end of 2008.⁹ These participants undergo physical examinations at the Rotterdam Study research facility and home interviews

every 3-4 years. Data is collected on health status, risk factors for various diseases common in the elderly, anthropometric characteristics, incident disease and cause-specific mortality.⁹ The Medical Ethics Committee of the Erasmus Medical Centre Rotterdam and the review board of the Dutch Ministry of Health, Welfare and Sport have approved this population-based cohort study, and all participants have provided written informed consent. For the purposes of this analysis, we combined data from cohorts RS-I (using the third visit in 1997-1999 as baseline), RS-II (baseline visit 2000-2001) and RS-III (baseline visit 2006-2009) of the Rotterdam Study.

Definition of type 2 diabetes mellitus, prediabetes and normoglycemia

As per the Rotterdam Study protocol and WHO guidelines, type 2 diabetes was defined as having a fasting plasma glucose level ≥ 7.0 mmol/L, a non-fasting plasma glucose ≥ 11.1 mmol/L, the use of oral anti-diabetic medication or insulin, treatment by diet with type 2 diabetes as an indication, or being registered with a general practitioner as having type 2 diabetes.^{10,11} Prediabetes was defined as a fasting plasma glucose level 6.0-6.9 mmol/L or a non-fasting plasma glucose level 7.7-11.1 mmol/L, in addition to absence of all type 2 diabetes criteria. Normoglycemia was defined as a fasting plasma glucose level ≤ 6.0 mmol/L and absence of any of the above criteria for prediabetes and type 2 diabetes. Fasting blood samples were obtained by means of venipuncture at the Rotterdam Study research facility. The samples were stored at -80°C in 5 mL aliquots. Within one week of sampling, glucose levels were measured by means of the glucose hexokinase method.¹² All measurements were performed at the clinical chemistry laboratory of Erasmus University Medical Center, Rotterdam.

Measurement of serum uric acid

Serum uric acid was determined in non-fasting blood samples, centrifuged for 10 minutes at 3,000 RPM and then stored for one week at -20°C . Uric acid activity was determined using a Kone Diagnostica reagent kit and a Kone auto-analyzer. After every 10 samples, 3 control samples were included to check calibration. If the average values of the control samples were not within 2.5% of the true value in each run of 100 samples, this run was repeated. Day-by-day variation had to be within 5% of this average value.

Covariates

In our study, the following covariates are considered: age, sex, body mass index (BMI), smoking status, daily alcohol intake, total serum cholesterol, serum HDL (high-density lipoprotein) cholesterol, systolic blood pressure, serum insulin, serum glucose, hypertension (defined as having a systolic blood pressure > 140 mmHg, a diastolic blood pressure > 100 mmHg or receiving blood-pressure lowering medication with hypertension

as an indication), physical activity, use of diuretics and estimated glomerular filtration rate (eGFR). Data on serum glucose, total serum cholesterol, serum HDL cholesterol, serum insulin, blood pressure and eGFR were obtained at baseline by means of venipuncture, performed during participants' visits to the Rotterdam Study research facility. Anthropometric characteristics were also recorded at the Rotterdam Study research facility. eGFR was calculated using the Chronic Kidney Disease Epidemiology Collaboration (CKD-EPI) equation.¹³ The disease status with respect to type 2 diabetes and prediabetes was ascertained through follow-up using general practitioners' records and hospital discharge letters, collected as part of the Rotterdam Study. Physical activity was assessed at baseline by means of a modified version of the Zutphen Study Physical Activity Questionnaire and the LASA Physical Activity Questionnaire.⁹ Metabolic equivalents of task (MET) hours per week were calculated based on time spent in light, moderate and vigorous activity. Data concerning the use of medication, alcohol consumption and smoking at baseline was obtained through Rotterdam Study home interviews and, for medication, consulting pharmacy dispensing records.

Statistical analysis

To determine the association between serum uric acid and risk of incident prediabetes or incident type 2 diabetes, Cox proportional hazards regression was performed with serum uric acid as the primary independent variable and either incident prediabetes or incident type 2 DM as the response variable. The timescale in these models is follow-up time in years from baseline to either of the clinical endpoints, death, loss-to-follow-up or January 1st, 2012. Models adjusted only for age, sex and cohort as well as multivariable-adjusted Cox models were designed. The confounders BMI, smoking status, daily alcohol intake, total serum cholesterol, serum HDL cholesterol, systolic blood pressure, serum insulin, serum glucose, hypertension status, physical activity, use of diuretics and eGFR, selected based on previous literature, were added to the models adjusted for age, sex and cohort incrementally. The covariates serum insulin level, serum glucose level, daily alcohol intake and physical activity were log-transformed in the analyses because they displayed non-normality. Non-linearity was accounted for by inclusion of polynomial terms in the regression models if they significantly improved model fit. Interaction of uric acid with age and sex was investigated by introducing the product of the variables age and sex with uric acid to the regression models. Five-fold multiple imputation was performed to account for missing values. The results of our analyses are presented as hazard ratios (HR) with corresponding 95% confidence intervals (95% CI). A p-value < 0.05 was considered statistically significant. Analyses were performed using SPSS Statistics version 21 (IBM Corp., Armonk, New York, USA) and R version 3.2.4 (The R foundation for Statistical Computing, Vienna, Austria).

RESULTS

The total study population eligible for analysis ($n = 8,367$) was divided into two mutually exclusive subgroups: a subgroup with normoglycemia at baseline ($n = 7,030$) and a subgroup with prevalent prediabetes at baseline ($n = 1,337$). The selection procedure of our study population and the subgroups is outlined in Figure 3.1.1. Baseline characteristics of the study population are presented in Table 3.1.1.

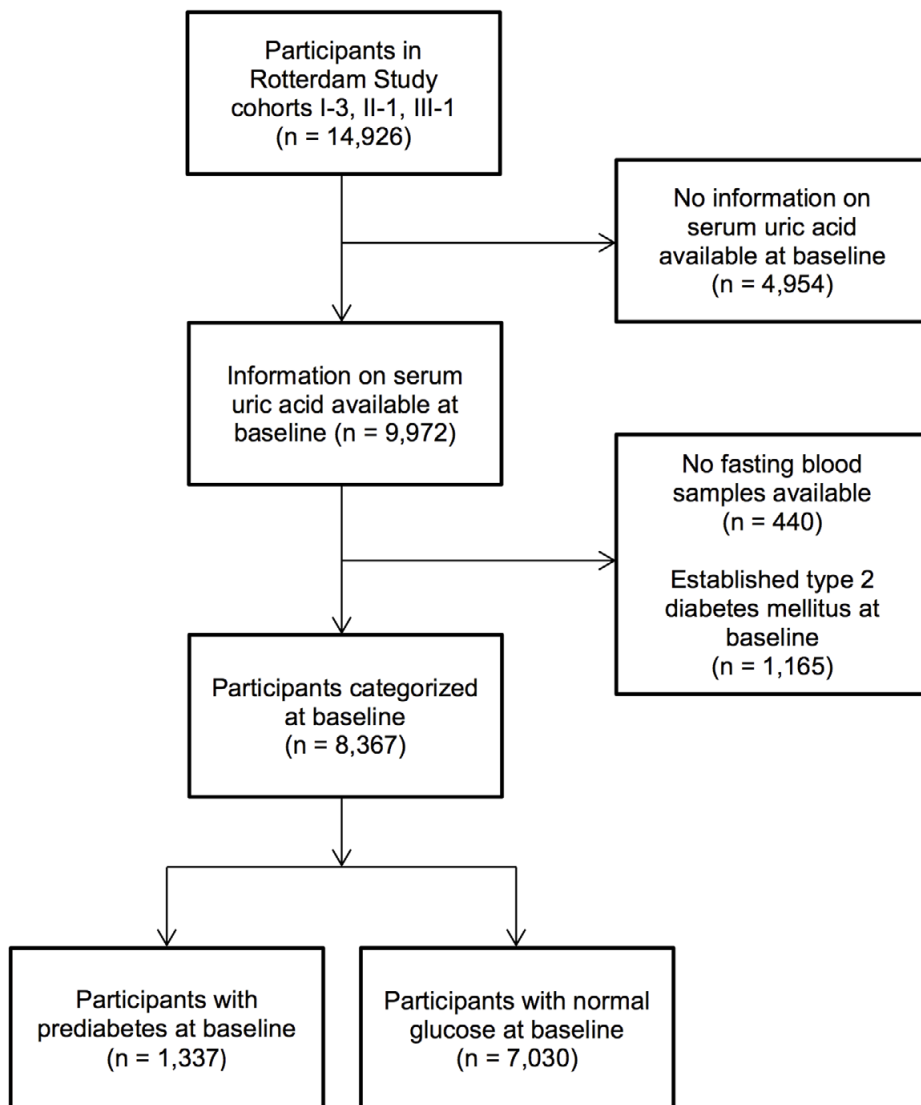


Figure 3.1.1. Selection of the study population.

Table 3.1.1. Baseline characteristics of the study population.

	Normoglycaemia at baseline (n = 7,030)	Missing data (%)	Prediabetes at baseline (n = 1,337)	Missing data (%)
Age (years)	64.2 (9.7)	0.0%	66.6 (9.4)	0.0%
Sex		0.0%		0.0%
Male	2,890 (41.1%)		665 (49.7%)	
Female	4,140 (58.9%)		672 (50.3%)	
Body Mass Index	26.7 (3.9)	0.7%	28.5 (4.4)	0.6%
Serum Total Cholesterol (mmol/L)	5.8 (1.0)	0.0%	5.8 (1.0)	0.2%
Serum HDL (mmol/L)	1.4 (0.4)	0.6%	1.3 (0.4)	0.8%
Systolic Blood Pressure (mmHg)	137.2 (20.5)	0.5%	145.4 (20.8)	0.2%
Serum Insulin (pmol/L) ¹	66.0 (44.0)	0.2%	93.0 (67.0)	0.1%
Alcohol Consumption (g/day) ^{1,2}	10.1 (12.6)	30.6%	13.7 (17.7)	35.2%
Current	6,008 (85.2%)	0.7%	1,154 (86.3%)	0.5%
Former or never	975 (14.1%)		176 (13.2%)	
Smoking		0.7%		0.4%
Current	1,236 (17.6%)		237 (17.7%)	
Former or never	5,794 (82.4%)		1,100 (82.3%)	
Hypertension ³		1.3%		0.7%
Yes	3,981 (56.6%)		1,000 (74.8%)	
No	3,049 (43.4%)		337 (25.2%)	
Use of diuretics		2.9%		3.1%
Yes	581 (8.3%)		199 (14.9%)	
Not	6,449 (91.7%)		1,138 (85.1%)	
Serum Glucose (mmol/L) ¹	5.3 (0.6)	0.0%	6.3 (0.4)	0.2%
Estimated Glomerular Filtration Rate (mL/min)	79.9 (15.7)	1.2%	77.4 (16.1)	0.5%
Metabolic Equivalents of Task (hours/week) ¹	71.6 (64.5)	11.6%	68.7 (64.0)	10.2%
Serum Uric Acid (mmol/L)	0.31 (0.07)	n/a	0.35 (0.08)	n/a

Variables are presented as mean (standard deviation) unless otherwise indicated. ¹Variable is presented as median (interquartile range). ²Median alcohol consumption applies only to active drinkers. ³Hypertension is defined as having a systolic blood pressure > 140 mmHg, a diastolic blood pressure > 100 mmHg or receiving blood-pressure lowering medication.

Over a mean follow-up time of 7.5 years, 1,071 individuals with normoglycemia at baseline developed prediabetes (incidence rate 20.2 per 1,000 person-years). In this analysis, the percentage of individuals who were lost to follow up was 0.6% (40 out of 7,030 individuals). The results of our analysis of the association between serum uric acid and incident prediabetes are presented in Table 3.1.2. We found a significant association between serum uric acid and incident prediabetes within individuals who were normoglycemic at baseline in a model adjusted only for age, sex and cohort

(HR 1.31 per SD increment, 95% CI 1.23; 1.40). This association was attenuated but remained significant in the multivariable-adjusted model (HR 1.10, 95% CI 1.01; 1.18). Performing separate analyses for men and women, we found that the association between serum uric acid and incident prediabetes was present in both men (HR 1.28, 95% CI 1.16; 1.41) and women (HR 1.34, 95% CI 1.23; 1.45) in models adjusted for age and cohort (Table 3.1.3). After multivariable adjustment, serum uric acid was significantly associated with incident prediabetes among women (HR 1.13, 95% CI 1.02; 1.25) but not among men (HR 1.08, 95% CI 0.96; 1.21). Exclusion of individuals who use diuretics or individuals with hypertension did not substantially change our findings (Table 3.1.4). The association was no longer statistically significant upon exclusion of individuals with a BMI \geq 25 (HR 1.14, 95% CI 0.98; 1.33). In the multivariable-adjusted model we also analyzed serum uric acid in quartiles, providing quartile-specific HRs relative to the first quartile (Figure 3.1.2).

Table 3.1.2. The association between serum uric acid and incidence of prediabetes and type 2 diabetes mellitus.

	Incident prediabetes in normoglycaemic individuals	P-value	Incident type 2 DM in prediabetic individuals	P-value
Model 1 ¹	1.31 (1.23; 1.40)	< 0.001	1.17 (1.06; 1.30)	0.002
Model 2 ²	1.30 (1.21; 1.40)	< 0.001	1.21 (1.08; 1.35)	0.001
Model 3 ³	1.10 (1.01; 1.18)	0.022	1.07 (0.94; 1.21)	0.330

Results are presented as Hazard Ratio (95% confidence interval) for a standard deviation increment in serum uric acid. ¹Model 1: adjusted for age, sex and Rotterdam Study cohort. ²Model 2: model 1 + hypertension status, serum total cholesterol, eGFR, MET-hours per week, systolic blood pressure and use of diuretics. ³Model 3: model 2 + daily alcohol intake, serum HDL, smoking status, BMI, serum glucose and serum insulin.

A total of 407 individuals with prediabetes at baseline developed type 2 DM over a mean follow-up time of 7.2 years (incidence rate 42.4 per 1,000 person-years). In this analysis, the percentage of individuals who were lost to follow up was 0.4% (6 out of 1,337 individuals). Serum uric acid was significantly associated with incident type 2 diabetes in individuals with prediabetes in a model adjusting only for age, sex and cohort (HR 1.17, 95% CI 1.06; 1.30), but this association weakened and was not statistically significant in the multivariable-adjusted model (HR 1.07, 95% CI 0.94; 1.21) (Table 3.1.2). In sex-specific analyses, the association was significant among men (HR 1.19, 95% CI 1.01; 1.40), and women (HR 1.18, 95% CI 1.03; 1.35) in models adjusted for age and cohort (Table 3.1.3). After multivariable adjustment, serum uric acid was significantly associated with incident type 2 diabetes among men (HR 1.23, 95% CI 1.01; 1.48) but not among women (HR 1.00, 95% CI 0.84; 1.19). Exclusion of diuretic users, individuals with hypertension or individuals with a BMI \geq 25 did not change

our findings (Table 3.1.4). No significant difference was observed in any serum uric acid quartile compared to the first quartile (Fig 2).

Table 3.1.3. The association between serum uric acid and incidence of prediabetes and type 2 diabetes mellitus, stratified by gender.

	Incident prediabetes in normoglycaemic individuals	P-value	Incident type 2 diabetes in prediabetic individuals	P-value
Men				
Model 1 ¹	1.28 (1.16; 1.41)	< 0.001	1.19 (1.01; 1.40)	0.038
Model 2 ²	1.26 (1.13; 1.40)	< 0.001	1.30 (1.09; 1.56)	0.004
Model 3 ³	1.08 (0.96; 1.21)	0.216	1.23 (1.01; 1.48)	0.039
Women				
Model 1 ¹	1.34 (1.23; 1.45)	< 0.001	1.18 (1.03; 1.35)	0.015
Model 2 ²	1.35 (1.23; 1.48)	< 0.001	1.19 (1.02; 1.38)	0.027
Model 3 ³	1.13 (1.02; 1.25)	0.024	1.00 (0.84; 1.19)	0.877

Results are presented as Hazard Ratio (95% confidence interval) for a standard deviation increment in serum uric acid. ¹Model 1: adjusted for age, sex and Rotterdam Study cohort. ²Model 2: model 1 + hypertension status, serum total cholesterol, eGFR, MET-hours per week, systolic blood pressure and use of diuretics. ³Model 3: model 2 + daily alcohol intake, serum HDL, smoking status, BMI, serum glucose and serum insulin.

Table 3.1.4. Subgroup analyses for the association between serum uric acid and incident prediabetes and incident type 2 diabetes mellitus.

	Incident prediabetes in normoglycaemic individuals	P-value	Incident type 2 DM in prediabetic individuals	P-value
Exclusion of participants who use diuretics	1.11 (1.02; 1.21)	0.016	1.05 (0.92; 1.21)	0.497
Exclusion of participants with hypertension	1.16 (1.00; 1.34)	0.045	1.14 (0.84; 1.56)	0.412
Exclusion of participants with a BMI \geq 25	1.14 (0.98; 1.33)	0.097	1.10 (0.75; 1.61)	0.647

Results are presented as multivariable-adjusted Hazard Ratios (95% confidence interval) for a standard deviation increment in serum uric acid, adjusted for age, sex, Rotterdam Study cohort, hypertension status, serum total cholesterol, eGFR, MET-hours per week, systolic blood pressure, use of diuretics, daily alcohol intake, serum HDL, smoking status, BMI, serum glucose and serum insulin.

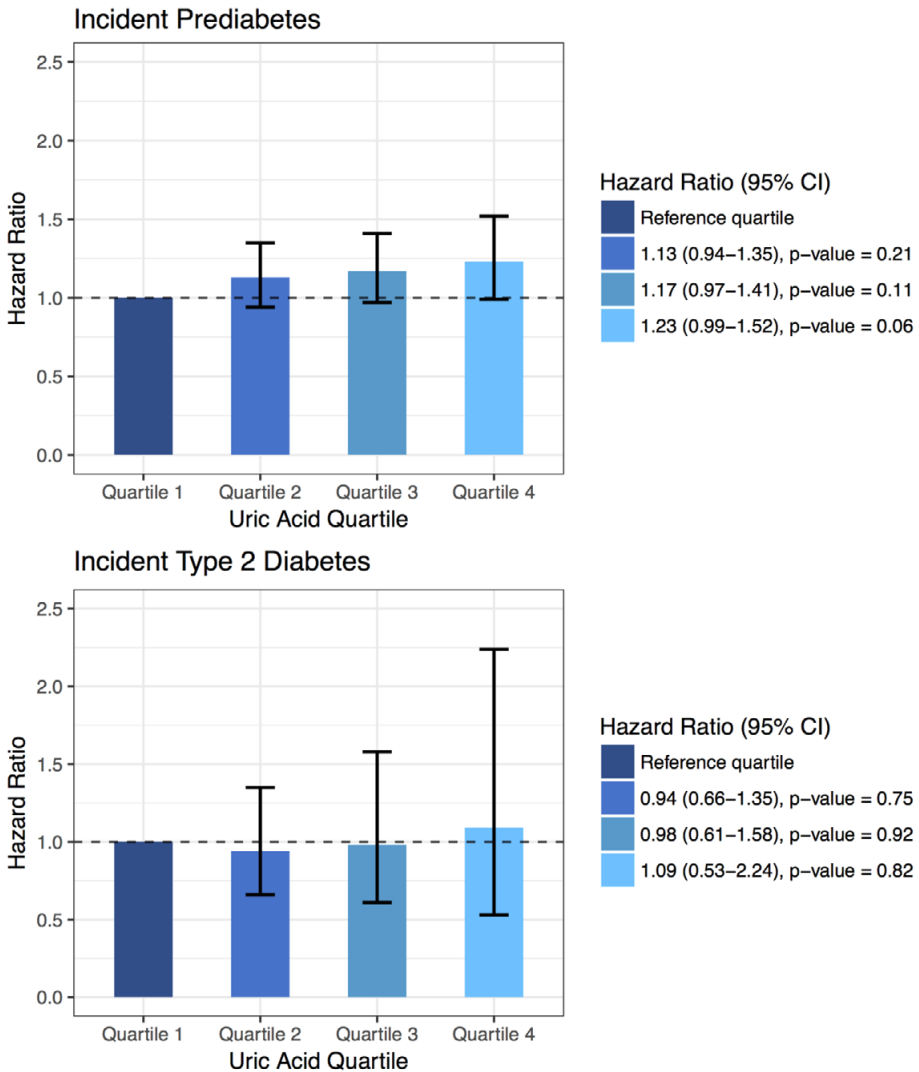


Figure 3.1.2. Quartile-specific hazard ratios for serum uric acid in association with incident prediabetes and incident type 2 diabetes mellitus.

DISCUSSION

We have found that higher serum uric acid levels are associated with an increased risk of incident prediabetes in individuals with normoglycemia aged 45 years or over, independently of confounders. No significant association was observed between serum uric acid and incident type 2 diabetes in individuals with prediabetes after multivariable adjustment.

The result with relation to incident prediabetes is consistent with previous research on this subject using impaired fasting glucose as an endpoint.¹⁴⁻¹⁷ This could indicate that serum uric acid is more closely associated with early-phase rather than late-phase mechanisms that play a role in the development of type 2 diabetes. Typically, insulin resistance impairs pancreatic β -cell physiology and compensatory mechanisms, thereby inducing β -cell dysfunction as a consequence.¹⁸ Insulin resistance could therefore be regarded as a reflection of early mechanisms that contribute to the development of type 2 diabetes, whereas β -cell dysfunction reflects the influence of late-stage mechanisms.¹⁹ Currently, not much evidence is available concerning the relation between serum uric acid and pancreatic β -cell function. Tang and colleagues found an independent positive association between serum uric acid levels and residual pancreatic β -cell function.²⁰ In their cross-sectional analysis of 1,021 individuals with type 2 diabetes, they observed that patients with higher serum uric acid had greater insulin secretion ability in early disease stages, but their residual β -cell function decayed more quickly. The authors suggest that this increased insulin secretion might be a compensatory mechanism to overcome initial insulin resistance. In addition, Shimodaira and colleagues observed a significant negative association between serum uric acid and disposition index, a measure of pancreatic β -cell function, in a cross-sectional analysis among non-diabetic Japanese women after adjustment for age, BMI, systolic blood pressure, HbA1c, serum triglyceride level, serum HDL and use of antihypertensive or antilipidemic drugs.²¹ However, no definitive conclusions regarding the association between serum uric acid and pancreatic β -cell function can be drawn at this point. Further population-based, prospective studies investigating this association are warranted. Although the association between serum uric acid and incident prediabetes was not significant among individuals with BMI < 25, this finding is most likely due to a lack of statistical power, because individuals with a BMI \geq 25 constitute over half of our sample size in this subgroup.

Serum uric acid has been investigated in relation to incident type 2 diabetes in individuals with impaired fasting glucose by Kramer and colleagues, who found a significant association (OR 1.75, 95% CI 1.1; 2.9) after adjusting for various confounders in study population with characteristics similar to ours.²² We were not able to replicate this finding in our analysis, in which we had a considerably larger sample available and were able to adjust for a more comprehensive set of confounding variables. It is possible that residual confounding in the previous study could account for this difference, because Kramer and colleagues were unable to adjust for smoking status and serum HDL. These covariates were particularly impactful in our multivariable-adjusted model. Excluding these covariates from the model yields an increase in the effect estimate (HR 1.13, 95% CI 1.00; 1.27) compared to the model which includes them (HR

1.07, 95% CI 0.94; 1.21). We also observe a steep decrease in the estimated hazard ratio for incident type 2 diabetes between model 2 and 3 in our analysis. The variable that is responsible for most of this decrease is serum HDL. It has been demonstrated that serum HDL is associated with plasma glucose levels and that it is strongly inversely associated with serum uric acid levels.^{23,24} Therefore, serum HDL can be regarded as a particularly strong confounder of this association.

Conflicting results have been reported in the literature about a possible sex-specific nature of the association between serum uric acid and impaired fasting glucose.^{16,17} In our study, we observe that serum uric acid is significantly associated with incident prediabetes among normoglycemic women, but not among normoglycemic men. Several studies report that the association between serum uric acid and glucose-related endpoints is especially pronounced among women.^{15,16,25,26} The difference between men and women with relation to incident prediabetes in our study can possibly be attributed to residual confounding. We also have fewer events among men (n = 439) than among women (n = 632) in this analysis, which might lead to more imprecision in our estimated hazard ratio for men.

In contrast to this finding relating to incident prediabetes, serum uric acid was significantly associated with incident type 2 diabetes among men with prediabetes, but not among women with prediabetes in our study after multivariable adjustment. This observation was despite the fact that the number of events was higher among women (n = 222) than among men (n = 185) in this analysis. No other study has investigated the relation between serum uric acid and type 2 diabetes specifically among men with established glucose intolerance. Our result might suggest that serum uric acid affects women more strongly in the early stages of glucose intolerance development, whereas it affects men more strongly in more advanced stages. Potential biological mechanisms underlying this phenomenon have not yet been investigated in the literature, and further research is warranted.

Our findings build on the conclusion of a report by Kodama and colleagues, who performed a meta-analysis on the association between serum uric acid and incident type 2 diabetes in populations not stratified by glucose tolerance status (normoglycemia or prediabetes) at baseline.²⁷ They conclude that serum uric acid is significantly associated with incident type 2 diabetes across 11 cohort studies, and that their result should encourage other studies to identify sub-populations for which the association might be especially important. We report that serum uric acid appears to be most strongly associated with the early stages of the development of type 2 diabetes. A similar meta-analysis by Jia and colleagues also found a positive association between

serum uric acid and a combined endpoint of incident impaired fasting glucose and incident type 2 diabetes.⁵ Our results further characterize the association between serum uric acid and glucose intolerance by treating incident prediabetes and incident type 2 diabetes as separate endpoints.

The strengths of our study include its prospective nature, which minimizes the chance of reverse causation, its long follow-up time and our ability to adjust for a large set of confounders. We provide a comprehensive overview of the relation between serum uric acid and different sub-stages on the spectrum between normoglycemia and type 2 diabetes. However, our study population consisted of mainly elderly individuals and roughly 95% of our participants were of Caucasian ethnicity. Therefore, our results cannot be generalized to populations with a different composition without further consideration. Finally, we cannot exclude the possibility of residual confounding, although the fact that we adjusted for many covariates should minimize the chance of this type of bias.

In conclusion, serum uric acid was independently and positively associated with incident prediabetes in individuals with normoglycemia but not with incident type 2 diabetes in individuals with prediabetes in a large population-based cohort of individuals aged 45 years and over. Our results indicate that serum uric acid might be more closely associated with early-phase pathogenic mechanisms that contribute to the development of type 2 diabetes rather than late-phase mechanisms.

ACKNOWLEDGMENTS

The dedication, commitment, and contribution of inhabitants, general practitioners, and pharmacists of the Ommoord district to the Rotterdam Study are gratefully acknowledged. We thank Symen Ligthart, Layal Chaker and Jolande Verkroost-van Heemst of Erasmus University Medical Center for their invaluable contribution to the collection and organization of the diabetes data.

REFERENCES

- 1 Kanbay M, Segal M, Afsar B, Kang DH, Rodriguez-Iturbe B, Johnson RJ. The role of uric acid in the pathogenesis of human cardiovascular disease. *Heart* 2013; **99**: 759–66.
- 2 Dehghan A, van Hoek M, Sijbrands EJ, Hofman A, Witteman JC. High serum uric acid as a novel risk factor for type 2 diabetes. *Diabetes Care* 2008; **31**: 361–2.
- 3 Wang T, Bi Y, Xu M, Huang Y, Xu Y, Li X *et al*. Serum uric acid associates with the incidence of type 2 diabetes in a prospective cohort of middle-aged and elderly Chinese. *Endocrine* 2011; **40**: 109–16.
- 4 Bhole V, Choi JW, Kim SW, de Vera M, Choi H. Serum uric acid levels and the risk of type 2 diabetes: a prospective study. *Am J Med* 2010; **123**: 957–61.
- 5 Jia Z, Zhang X, Kang S, Wu Y. Serum uric acid levels and incidence of impaired fasting glucose and type 2 diabetes mellitus: a meta-analysis of cohort studies. *Diabetes Res Clin Pr* 2013; **101**: 88–96.
- 6 Lv Q, Meng XF, He FF, Chen S, Su H, Xiong J *et al*. High serum uric acid and increased risk of type 2 diabetes: a systemic review and meta-analysis of prospective cohort studies. *PLoS One* 2013; **8**: e56864.
- 7 Wu AH, Gladden JD, Ahmed M, Ahmed A, Filippatos G. Relation of serum uric acid to cardiovascular disease. *Int J Cardiol* 2016; **213**: 4–7.
- 8 American Diabetes Association. Report of the Expert Committee on the Diagnosis and Classification of Diabetes Mellitus. *Diabetes Care* 1997; **20**: 1183–97.
- 9 Hofman A, Brusselle GGO, Darwish Murad S, van Duijn CM, Franco OH, Goedegebure A *et al*. The Rotterdam Study: 2016 objectives and design update. *Eur J Epidemiol* 2015; **30**: 661–708.
- 10 World Health Organization. Definition and Diagnosis of Diabetes Mellitus and Intermediate Hyperglycemia: Report of a WHO/IDF Consultation. 2006; : 3.
- 11 Ligthart S, van Herpt TTW, Leening MJG, Kavousi M, Hofman A, Stricker BHC *et al*. Lifetime risk of developing impaired glucose metabolism and eventual progression from prediabetes to type 2 diabetes: a prospective cohort study. *Lancet Diabetes Endocrinol* 2016; **4**: 44–51.
- 12 Neeley WE. Simple Automated Determination of Serum or Plasma Glucose by a Hexokinase/Glucose-6-Phosphate Dehydrogenase Method. *Clin Chem* 1972; **18**: 509–515.
- 13 Levey AS, Stevens LA, Schmid CH, Zhang YL, Castro AF, Feldman HI *et al*. A new equation to estimate glomerular filtration rate. *Ann Intern Med* 2009; **150**: 604–612.
- 14 Krishnan E, Pandya BJ, Chung L, Hariri A, Dabbous O. Hyperuricemia in young adults and risk of insulin resistance, prediabetes, and diabetes: a 15-year follow-up study. *Am J Epidemiol* 2012; **176**: 108–16.
- 15 Meisinger C, Doring A, Stockl D, Thorand B, Kowall B, Rathmann W. Uric acid is more strongly associated with impaired glucose regulation in women than in men from the general population: the KORA F4-Study. *PLoS One* 2012; **7**: e37180.
- 16 Kawamoto R, Tabara Y, Kohara K, Kusunoki T, Abe M, Miki T. Serum uric acid is more strongly associated with impaired fasting glucose in women than in men from a community-dwelling population. *PLoS One* 2013; **8**: e65886.
- 17 Liu Y, Jin C, Xing A, Liu X, Chen S, Li D *et al*. Serum uric acid levels and the risk of impaired fasting glucose: a prospective study in adults of north China. *PLoS One* 2013; **8**: e84712.
- 18 Cerf ME. Beta cell dysfunction and insulin resistance. *Front Endocrinol Lausanne* 2013; **4**: 37.

- 19 Martin BC, Warram JH, Krolewski AS, Bergman RN, Soeldner JS, Kahn CR. Role of glucose and insulin resistance in development of type 2 diabetes mellitus: results of a 25-year follow-up study. *Lancet* 1992; **340**: 925–9.
- 20 Tang W, Fu Q, Zhang Q, Sun M, Gao Y, Liu X *et al.* The association between serum uric acid and residual beta-cell function in type 2 diabetes. *J Diabetes Res* 2014; **2014**: 709691.
- 21 Shimodaira M, Niwa T, Nakajima K, Kobayashi M, Hanyu N, Nakayama T. The relationship between serum uric acid levels and beta-cell functions in nondiabetic subjects. *Horm Metab Res* 2014; **46**: 950–4.
- 22 Kramer CK, von Muhlen D, Jassal SK, Barrett-Connor E. Serum uric acid levels improve prediction of incident type 2 diabetes in individuals with impaired fasting glucose: the Rancho Bernardo Study. *Diabetes Care* 2009; **32**: 1272–3.
- 23 Drew BG, Duffy SJ, Formosa MF, Natoli AK, Henstridge DC, Penfold SA *et al.* High-Density Lipoprotein Modulates Glucose Metabolism in Patients With Type 2 Diabetes Mellitus. *Circulation* 2009; **119**: 2103–2111.
- 24 Peng T-C, Wang C-C, Kao T-W, Chan JY-H, Yang Y-H, Chang Y-W *et al.* Relationship between Hyperuricemia and Lipid Profiles in US Adults. *BioMed Res Int* 2015; **2015**: e127596.
- 25 Yamada T, Fukatsu M, Suzuki S, Wada T, Joh T. Elevated serum uric acid predicts impaired fasting glucose and type 2 diabetes only among Japanese women undergoing health checkups. *Diabetes Metab* 2011; **37**: 252–8.
- 26 Kivity S, Kopel E, Steinlauf S, Segev S, Sidi Y, Olchovsky D. The association between serum uric acid and diabetes mellitus is stronger in women. *J Womens Health Larchmt* 2013; **22**: 782–9.
- 27 Kodama S, Saito K, Yachi Y, Asumi M, Sugawara A, Totsuka K *et al.* Association between serum uric acid and development of type 2 diabetes. *Diabetes Care* 2009; **32**: 1737–1742.