



Long-term Cognitive Implications of Intrauterine Hyperglycemia in Adolescent Offspring of Women With Type 1 Diabetes (the EPICOM Study)

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OBJECTIVE

Exposure to maternal diabetes in utero may have a negative impact on the developing brain. The objective was to examine long-term cognitive consequences of intrauterine hyperglycemia in adolescent offspring of women with type 1 diabetes and to ascertain a possible association with maternal HbA_{1c}.

RESEARCH DESIGN AND METHODS

Offspring of a prospectively followed cohort of women with type 1 diabetes ($n = 277$) participated in a follow-up examination at the age of 13–19 years. A control group from the background population was identified ($n = 301$). Cognitive function was evaluated using Reynolds Intellectual Assessment Scales and classified into indices of composite intelligence, verbal and nonverbal intelligence, and composite memory. Frequencies of reading and writing problems and attendance to classes for children with learning difficulties were assessed.

RESULTS

Offspring of women with type 1 diabetes scored lower in all normalized and standardized intelligence indices compared with controls: composite intelligence (95.7 vs. 100, $P = 0.001$), verbal intelligence (96.2 vs. 100, $P = 0.004$), nonverbal intelligence (96.4 vs. 100, $P = 0.008$), and composite memory (95.7 vs. 100, $P = 0.001$). A higher frequency of diabetes-exposed offspring had parent-reported learning difficulties in primary school. Differences between groups remained after adjustment for confounders and potential mediators. We found no direct association between maternal HbA_{1c} and offspring cognitive function in the exposed group.

CONCLUSIONS

Adolescent offspring of women with type 1 diabetes had lower cognitive function compared with a control group, also after adjustment for confounders and potential mediators. These differences may reflect direct harmful effects of maternal diabetes on neurodevelopment in the offspring.

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Intrauterine hyperglycemia has both short-term and long-term implications on offspring morbidity and mortality, which are associated with the degree of maternal glycemic control before and during pregnancy (1–9).

Development of the central nervous system is an array of complex processes, initiated in the early embryonic period continuing until late adolescence and adulthood (10). These processes are known to be vulnerable to a large number of adverse environmental factors associated with an increased risk of neurological and psychiatric disorders in later life (11–16).

A hyperglycemic intrauterine environment may exert a negative impact on development of the fetal brain, with long-term implications for cognitive function. This association may reflect a direct harmful influence of hyperglycemia and/or the effects of potential mediators associated with maternal diabetes in pregnancy: preterm birth and complications in pregnancy, at delivery, and in the neonatal period. Episodes of severe hypoglycemia or ketoacidosis may also be harmful to the offspring brain.

The potential association between maternal diabetes and cognitive function in the offspring has been investigated in previous studies (17–26). However, these studies are based on diverse populations with diabetes with different follow-up times and various assessments of cognitive function, resulting in diverging conclusions. Some studies report a negative association, with lower scores in cognitive tests and lower school performance (18,22,24), while others find no association after adjustment for confounders (17,20,23) or even a positive association (21,25,26). A Danish register study found no difference in academic achievement in primary school between offspring exposed to maternal type 1 diabetes ($n = 707$) and matched control subjects ($n = 60,341$), although a negative association between maternal HbA_{1c} in pregnancy and academic achievement in offspring exposed to maternal diabetes was reported (19).

In this study we performed a follow-up examination of adolescent offspring of a well-characterized cohort of Danish women with type 1 diabetes to assess the cognitive function compared with a control group in order to evaluate

the long-term cognitive consequences of intrauterine hyperglycemia. We used measurements of maternal HbA_{1c} before and during pregnancy, as well as episodes of severe hypoglycemia and ketoacidosis, to evaluate potential associations between maternal metabolic control and cognitive function in the diabetes-exposed offspring.

RESEARCH DESIGN AND METHODS

EPICOM (EPIgenetic, genetic and environmental effects on COgnitive and Metabolic functions in offspring of mothers with type 1 diabetes) is a Danish prospective nationwide follow-up study focusing on the long-term effects of intrauterine hyperglycemia (9). During 1993–1999 all pregnant women with type 1 diabetes in Denmark were prospectively reported to a central register in the Danish Diabetes Association ($n = 1,215$) (1). The women delivered at one of eight centers responsible for antenatal care and delivery of pregnant women with diabetes in Denmark at that time. Data on maternal demography, diabetes status, and pregnancy outcome were reported to the register after delivery. All deliveries after 24 gestational weeks were included. The coverage of reported pregnancies in women with type 1 diabetes in Denmark in this period was 75–93%.

Participants

The offspring of women with type 1 diabetes in the register with available data were invited to participate in a follow-up examination at the age of 13–19 years (Supplementary Fig. 1). Only singletons and one child per mother were invited ($n = 746$). With 452 nonrespondents/declines to participate and exclusion of sixteen adolescents, a total of 278 adolescent offspring of women with type 1 diabetes participated (index group). Exclusions were because of maternal diagnosis of type 1 diabetes reclassified to maturity-onset diabetes of the young or type 2 diabetes ($n = 12$), no contact between mother and child ($n = 2$), drug abuse ($n = 1$), and pregnancy ($n = 1$). We identified a control group through the Danish Central Civil Registration System, matched according to sex, age, and postal code (marker of socioeconomic status) ($n = 1,920$). A total of 303 participated, and 1,609 did not respond or declined to participate. Eight

offspring were excluded for the following reasons: adopted child ($n = 4$), birthplace outside of Denmark ($n = 1$), or the obstetric record revealed gestational diabetes mellitus ($n = 3$). The cognitive tests were completed by 277 (37.1%) exposed and 301 (15.7%) unexposed offspring. Details about the inclusion process and follow-up have recently been published (9).

The protocol was in accordance with the Declaration of Helsinki and approved by the local ethics committee (M-20110239). Written informed consent was obtained from all participants or their parents if the participant was younger than 18 years.

At Follow-up

The participants were examined at one of three Danish University Hospitals (Copenhagen, Odense, and Aarhus) from April 2012 to October 2013. We used Reynolds Intellectual Assessment Scales (RIAS) to evaluate cognitive function. RIAS were selected for their short administration time (30–40 min) and the possibility of applying the same test to all participants, since RIAS are normed in the ages from 3 to 94 years. RIAS constitute a valid test of intelligence and memory with adequate correlation with Wechsler's Intelligence Scale for Children and Wechsler's Adult Intelligence Scale (27,28).

RIAS consist of two verbal and two nonverbal subtests, providing estimates of verbal and nonverbal intelligence. Age-adjusted scores from all four subtests are summed to derive a measure of composite intelligence. Composite memory was assessed using two supplementary RIAS subtests. For ease of interpretation, test scores were normalized and standardized to a mean of a 100 and an SD of 15 in the control group. Cognitive function was evaluated by exposure-blinded testers. Prior to the follow-up examination parents or parents and offspring together completed a questionnaire about learning difficulties in primary school and parental education.

Variables

Outcomes and Exposure

Primary outcomes were composite, verbal, and nonverbal intelligence and composite memory assessed by RIAS. Secondary outcomes were learning difficulties in primary school, assessed by parent-reported

reading and writing problems and attendance in classes for children with learning problems in Danish or mathematics at any time in primary school.

Exposure was maternal type 1 diabetes in fetal life.

Maternal Predictors

We used measurements of HbA_{1c} (preconceptional and first, second, and third trimester) to evaluate maternal glycaemic control during pregnancy. Episodes of severe hypoglycemia in pregnancy were defined as hypoglycemia requiring assistance from another person. The definition of ketoacidosis in pregnancy was an event of plasma bicarbonate <15 mmol/L and hospitalization. Information about glycaemic control and glycaemic events was taken from the register in the Danish Diabetes Association (1).

Parental educational level was estimated from the questionnaire completed by the offspring and their parents. It was calculated as the sum of maternal and paternal years in school and in higher education.

Maternal age at delivery, parity, and information about complications in pregnancy were retrieved from the Danish Diabetes Association register (index group) or from obstetric records (control group). Pregnancy complications were defined as occurrence of hydramnios (clinical diagnosis) or preeclampsia (blood pressure >140/90 mmHg and proteinuria).

Information on smoking in pregnancy and parental intelligence was not available. In addition we were not able to collect sufficient data on mode of delivery in the control group, and these variables were not included in our analysis.

Offspring Predictors

Data about gestational age, birth weight, congenital malformations, and neonatal complications were extracted from the register (index group) or from obstetric records (control group). Neonatal complications were combined and defined as hypoglycemia (clinical signs that disappeared after administration of glucose), jaundice (treated with phototherapy), respiratory distress (need for assisted ventilation, continuous positive airway pressure >1 h after birth), Apgar 5 <7, and systemic infections (systemic antibiotics). Birth weight SD scores (bwSDS) were calculated using intrauterine growth curves adjusted for gestational age and sex (29).

Potential Mediators and Confounders

Potential confounders were offspring sex, age at follow-up, parity, parental educational length, and maternal age at delivery. Gestational age, bwSDS, pregnancy complications, and neonatal complications were considered potential mediators between intrauterine hyperglycemia and offspring cognitive function.

Statistics

Normally distributed continuous data are presented as mean and SD. Continuous data with skewed distribution are presented as median and interquartile range. Student *t* test and Mann-Whitney, χ^2 , and Fisher exact tests were used to compare groups where appropriate.

For adjustment for the effect of confounders and mediators on offspring cognitive function, multivariate linear regression analyses were performed, with exposure as the independent variable and composite intelligence and composite memory as outcome measures. The results are presented as regression coefficients (β) corresponding to the mean difference in cognitive test score between groups with 95% CI.

Multivariate logistic regression analyses were performed when the outcome measures were learning difficulties. Results were reported as odds ratio (OR) and 95% CI.

We fitted a simple linear model in the index group to test the association between maternal glycaemic control in pregnancy (HbA_{1c}) and offspring cognitive function. Offspring test scores were the outcome measure, and HbA_{1c} was included as a continuous exposure variable; the regression coefficient (β) expresses the change in test score corresponding to a 1% increase in HbA_{1c}. Statistical analyses were performed using IBM SPSS Statistics, version 22, with a significance level of 0.05.

RESULTS

A total of 277 (37.1%) diabetes-exposed offspring (index group) with a mean age of 16.6 years, and 301 (15.7%) unexposed offspring (control group) with a mean age of 16.8 years, participated in the follow-up examination of cognitive function (Supplementary Fig. 1). All participants were born in Denmark, and 98.8% were of white European ethnicity. Baseline differences between participants and nonparticipants in the index group

were found according to maternal preconceptional HbA_{1c} (first trimester or latest prepregnancy HbA_{1c} in case of missing value) and bwSDS. Participants had a lower maternal HbA_{1c} (7.3% [56 mmol/mol] vs. 7.5% [58 mmol/mol], $P = 0.015$) and a higher bwSDS (1.8 vs. 1.5, $P = 0.016$) compared with nonparticipants. Participants and nonparticipants from the index group were similar with respect to parity, maternal prepregnancy age, maternal prepregnancy BMI, duration of diabetes, and HbA_{1c} in the second and third trimester.

Baseline and follow-up characteristics of included offspring are shown in Table 1. Differences between index and control offspring at baseline were found for gestational age, bwSDS, and proportions of neonatal complications, neonatal hypoglycemia, congenital malformations, nulliparity, and pregnancy complications. The groups did not differ with regard to parental educational length.

In the index group the mean maternal diabetes duration at conception was 12.5 (SD 8.3) years. Frequencies of pregestational proliferative retinopathy and macroalbuminuria were 6.9% and 4.7%, respectively.

Intelligence and Memory Indices

Index offspring had lower scores on all cognitive measures compared with the control group: composite intelligence (95.7 vs. 100, $P = 0.001$), verbal intelligence (96.2 vs. 100, $P = 0.004$), nonverbal intelligence (96.4 vs. 100, $P = 0.008$), and composite memory (95.7 vs. 100, $P = 0.001$) (Table 2). Scores on composite intelligence and composite memory were still lower in the diabetes-exposed offspring after adjustment for known confounders and potential mediators (Table 3).

Furthermore, in the index and control groups combined, age at follow-up ($\beta = 1.23$, 95% CI 0.28–2.19, $P = 0.01$), parental educational length ($\beta = 0.92$, 95% CI 0.54–1.30, $P < 0.001$), maternal age at delivery ($\beta = 0.56$, 95% CI 0.15–0.96, $P = 0.007$), and bwSDS ($\beta = 1.19$, 95% CI 0.27–2.11, $P = 0.01$) were independent positive predictors of composite intelligence, while multiparity was an independent negative predictor ($\beta = -4.87$, 95% CI -8.23 to -1.50, $P = 0.005$). Independent positive predictors of composite memory were parental educational length ($\beta = 0.59$, 95% CI 0.23–0.95, $P = 0.001$) and

Table 1—Baseline and follow-up characteristics in adolescent offspring exposed to maternal type 1 diabetes and in an unexposed control group

	<i>n</i> *	Exposed	Unexposed	<i>P</i>
Baseline				
<i>N</i>		277	301	
Male sex (%)	277/301	40.8% (113)	39.9% (120)	0.820
Gestational age at delivery (days) [†]	260/220	260 (251–266)	280 (273–287)	<0.001
Preterm delivery (<37 weeks)	260/220	41.2% (107)	4.1% (9)	<0.001
Preterm delivery (<34 weeks)	260/220	10.4% (27)	0.5% (1)	<0.001
Birth weight (g) [†]	263/225	3,680 (3,190–4,090)	3,580 (3,300–3,825)	0.119
bwSDS [†]	258/220	1.78 (0.38–3.27)	−0.04 (−0.60 to 0.62)	<0.001
Neonatal complications [‡]	260/198	49.2% (128)	5.1% (10)	<0.001
Neonatal hypoglycemia	265/209	32.5% (86)	0.5% (1)	<0.001
Congenital malformations	265/211	3.8% (10)	0.0% (0)	0.004
Maternal age at delivery (years)	277/301	30.0 (4.1)	29.9 (4.3)	0.783
Nulliparity	266/221	60.2% (160)	42.1% (93)	<0.001
Maternal BMI (kg/m ²) [†]	223/186	23.0 (21.3–25.2)	22.6 (20.6–24.7)	0.077
Pregnancy complications [§]	265/190	30.9% (82)	10.5% (20)	<0.001
Follow-up				
Offspring age at follow-up (years) [†]	277/301	16.6 (15.3–18.0)	16.8 (15.3–18.2)	0.396
Head circumference (cm)	277/301	56.0 (1.76)	56.1 (1.66)	0.495
Parental educational length (years)	265/282	27.6 (4.2)	28.2 (4.4)	0.129

Data are mean (SD) or proportion (*n*) unless otherwise indicated. *Exposed/unexposed. Numbers differ between variables because of missing data.

[†]Data are presented as median (interquartile range) when not normally distributed. [‡]Hypoglycemia, jaundice, respiratory distress, Apgar 5 <7, systemic infections. [§]Hydranmios, preeclampsia. ^{||}Sum of parents' total educational length in years.

maternal age at delivery ($\beta = 0.46$, 95% CI 0.07–0.84, $P = 0.02$). Male sex ($\beta = -5.06$, 95% CI -8.14 to -1.98 , $P = 0.001$) was an independent negative predictor of the composite memory score.

Learning Difficulties

Differences between groups were not found for reading and writing problems in primary school, but index offspring had a higher frequency of learning difficulties in the subjects Danish (23.3 vs. 13.8%) and mathematics (16.4 vs. 7.7%) (Table 2).

Similarly, in crude analyses the ORs for learning difficulties were higher in index offspring compared with control

offspring (Table 3). OR for learning difficulties in mathematics remained higher in index offspring after adjustment for confounders and possible mediators. The groups did not differ regarding learning difficulties in Danish after adjustment for confounders ($P = 0.055$) and mediators ($P = 0.159$).

Exposure to maternal diabetes was the only independent positive predictor of learning difficulties in mathematics (OR 2.68, 95% CI 1.09–6.61, $P = 0.032$) but did not predict difficulties in Danish. Independent negative predictors were parental educational level for both mathematics (OR 0.89, 95% CI 0.83–

0.97, $P = 0.005$) and Danish (OR 0.90, 95% CI 0.84–0.96, $P = 0.002$) and bwSDS for mathematics (OR 0.79, 95% CI 0.66–0.94, $P = 0.008$).

Maternal Glycemic Control

Analysis was restricted to the index group, since HbA_{1c} measurements were limited to women with diabetes in pregnancy. Numbers of measurements pregestational ($n = 233$) and in first ($n = 252$), second ($n = 259$), and third ($n = 252$) trimester varied because of missing data. There were no associations between maternal HbA_{1c} measurements and intelligence or memory indices in crude or adjusted analysis (Supplementary Table 1).

Offspring of women with episodes of severe hypoglycemia in pregnancy ($n = 32$) had lower, although not statistically significant, scores on all intelligence indices compared with diabetes-exposed offspring without hypoglycemic episodes (Table 4).

In line with this, maternal episodes of ketoacidosis ($n = 5$) were associated with markedly lower offspring scores in all intelligence and memory indices (Table 4). Scores in composite intelligence (81.6 vs. 95.5, $P = 0.078$) and composite memory (81.6 vs. 96.0, $P = 0.035$) were >1 SD below the mean of the background population. Because of the limited number of women with severe hypoglycemic and ketoacidotic episodes, adjustments for

Table 2—Cognitive function in adolescent offspring of women with type 1 diabetes ($n = 277$) and an unexposed control group ($n = 301$)

	Exposed	Unexposed	<i>P</i>
Intelligence indices			
Composite Intelligence Index	95.7 (17.3)	100 (15)	0.001
Verbal Intelligence Index	96.2 (16.8)	100 (15)	0.004
Nonverbal Intelligence Index	96.4 (17.0)	100 (15)	0.008
Composite Memory Index	95.7 (15.3)	100 (15)	0.001
Learning difficulties*			
Reading problems	22.4% (62)	18.7% (56)	0.269
Writing problems	19.3% (52)	16.3% (48)	0.353
Learning difficulties, Danish	23.3% (64)	13.8% (41)	0.003
Learning difficulties, mathematics	16.4% (45)	7.7% (23)	0.001

Data are means (SD) or proportion (*n*). Scores in intelligence and memory indices are based on RIAS. Scores in intelligence and memory indices in the control group were standardized to a mean (SD) of 100 (15). *Parent-reported by questionnaire (by parents or parents and offspring together).

Table 3—Regression analysis on Composite Intelligence Index and Composite Memory Index scores and learning difficulties in primary school in offspring of women with type 1 diabetes (n = 277) compared with an unexposed control group (n = 301)

Composite Intelligence Index			
Model	β	95% CI	P
Crude	-4.35	(-6.99 to -1.71)	0.001
1	-4.12	(-6.97 to -1.27)	0.005
2	-7.60	(-12.11 to -3.09)	0.001
Composite Memory Index			
Model	β	95% CI	P
Crude	-4.30	(-6.78 to -1.82)	0.001
1	-3.73	(-6.52 to -0.95)	0.009
2	-4.97	(-9.27 to -0.67)	0.024
Learning difficulties, Danish*			
Model	OR	95% CI	P
Crude	1.90	(1.23 to 2.93)	0.004
1	1.64	(0.99 to 2.72)	0.055
2	1.78	(0.80 to 3.98)	0.159
Learning difficulties, Mathematics*			
Model	OR	95% CI	P
Crude	2.34	(1.37 to 3.98)	0.002
1	2.26	(1.20 to 4.26)	0.012
2	2.68	(1.09 to 6.61)	0.032

The regression coefficient (β) is the mean difference between the exposed offspring and the control group. Scores in intelligence and memory indices are based on RIAS. Model 1: adjustment for confounders (offspring sex, age at follow-up, parity, parental educational length, maternal age at delivery). Model 2: adjustment for model 1 confounders plus adjustment for potential mediators (neonatal complications, pregnancy complications, gestational age, bwSDS). *Parent reported by questionnaire (by parents or parents and offspring together).

confounders and mediators were not performed.

CONCLUSIONS

In this large nationwide cohort of adolescent offspring we found that those exposed to maternal diabetes had impaired cognitive function compared

with a control group. Differences between groups could not be explained by confounders or mediators, indicating a harmful effect of intrauterine hyperglycemia. However, we were not able to demonstrate any direct association between maternal HbA_{1c} in pregnancy and cognitive performance in the offspring.

Table 4—Association between maternal episodes of severe hypoglycemia or ketoacidosis in pregnancy and offspring scores in RIAS in offspring of women with type 1 diabetes

	Present	Not present	P
Severe hypoglycemia in pregnancy	32	221	
Composite Intelligence Index	89.7 (19.0)	95.9 (17.0)	0.06
Verbal Intelligence Index	90.8 (18.8)	96.5 (16.7)	0.07
Nonverbal Intelligence Index	91.5 (18.6)	96.6 (16.7)	0.110
Composite Memory Index	93.4 (17.1)	95.9 (14.9)	0.381
Model	5	249	
Composite Intelligence Index	81.6 (19.5)	95.5 (17.3)	0.078
Verbal Intelligence Index	82.3 (12.7)	96.0 (16.9)	0.073
Nonverbal Intelligence Index	85.8 (26.2)	96.4 (17.0)	0.172
Composite Memory Index	81.6 (17.0)	96.0 (15.1)	0.035

Data are presented as n or mean (SD). Numbers differ between variables because of missing data.

An apparent limitation is the risk of selection bias because of the low participation rate (index 37.1% and control subjects 15.7%).

Previous studies, using various assessments of cognitive function, have reported lower cognitive performance in offspring exposed to maternal diabetes (18,20,24) but, in most cases, with limitations due to either study size or lack of differentiation between diabetes types. The inclusion of offspring in our study was restricted to offspring of women with type 1 diabetes. It is a strength, since different diabetes types may have diverse metabolic presentations in pregnancy.

In a study of adult offspring of Danish women with type 1 diabetes, differences in intelligence scores between diabetes-exposed offspring and control subjects were similar, as suggested in our study, with many shared independent predictors of offspring cognitive function (17). However, Clausen et al. (17) found no association between exposure and cognitive function after adjustment for known confounders, which might reflect the smaller study population (diabetes-exposed offspring n = 158) compared with our cohort (diabetes-exposed offspring n = 277).

Adjustment for confounders and mediators in our study did not change the association between intrauterine diabetes exposure and offspring cognitive function. Thus, our results imply a direct influence of intrauterine hyperglycemia on offspring cognitive function not accounted for by known confounders or potential mediators.

We showed differences between the diabetes-exposed and -unexposed groups in terms of learning difficulties in primary school. Information about learning difficulties was parent-reported, and some inaccuracy is potentially associated with this variable. We were not able to validate this information with information from other sources. Learning difficulties are often associated with other cognitive impairments, and it would be interesting to ascertain the frequency of attention deficit disorders and other aberrant neurodevelopment in the offspring. Recently, autism spectrum disorders have been suggested to be associated with maternal gestational diabetes mellitus (30).

Our group has previously shown that diabetes-exposed offspring and a control

group had similar school achievement in primary school in a register study based on the EPICOM population (19). However, there was an inverse association between maternal glycemic control and offspring school grades, which may reflect advanced maternal executive skills related to management of a complex chronic disease. The discrepancy between findings in the register-based study and the current study could be explained by greater measurement precision and sensitivity of intelligence tests compared with school grades. However, it is reassuring that the offspring attain school grades in primary school similar to those of unexposed offspring despite lower cognitive function. This difference may theoretically be explained by the larger proportion of diabetes-exposed offspring attending classes for children with learning problems in primary school observed in our study, which may help students attain higher school grades. Finally, the discrepancy between findings could be a result of sample bias, since only a third of the invited population participated in the current study. A future study of the highest attained educational level in adult offspring would be valuable to evaluate whether diabetes-exposed offspring are able to compensate for the lower cognitive function after primary school.

A few recent studies report findings of a positive effect of a diabetic intrauterine environment on offspring cognitive function (21,25,26), all with limited statistical power. A study, using Swedish register data to evaluate cognitive performance in male siblings discordant for exposure to maternal diabetes, found diabetes in pregnancy associated with lower academic achievement at age 16 years and lower intelligence quotient at conscription in nonsiblings but not in siblings discordant for maternal diabetes exposure (25). The association between maternal diabetes and intelligence quotient at conscription within siblings was positive but small and nonsignificant.

Bonilla et al. (26) applied a Mendelian randomization strategy and identified a discrete positive association between maternal genetic risk scores for type 2 diabetes and offspring intelligence at 8 years of age. The authors suggest the possibility of beneficial effects of increased glucose flow related to risk genes to the child's intrauterine neurological development, shifting to an

adverse effect after establishment of a clinical diabetic disease.

Maternal Glycemic Control

Recommendations of glycemic control in the 1990s, when the register of pregnant women with type 1 diabetes was established, allowed higher levels of HbA_{1c} than current guidelines. An HbA_{1c} level in pregnancy <7% (53 mmol/mol) was considered acceptable; thus, HbA_{1c} levels in our cohort were higher than we would expect today (31). In a Danish study using cognitive scores at conscription, HbA_{1c} was negatively associated with offspring cognitive function, but when HbA_{1c} levels were <7% (53 mmol/mol) cognitive function was the same as in control subjects (23). Mean maternal HbA_{1c} in our cohort was >7% pregestational and in first trimester.

However, we were not able to find any association between maternal HbA_{1c} levels and test scores in the index offspring, which may indicate that additional factors other than glucose are responsible in the link between intrauterine hyperglycemia and offspring cognitive function.

The validity of HbA_{1c} as measurement of overall glycemic control in pregnancy could be another explanation. HbA_{1c} measurements reflect the mean glycaemic level but with more impact of the recent glucose levels (32). The glucose levels change physiologically during pregnancy, resulting in different physiological levels dependent on the timing of the measurement in each trimester. Furthermore, HbA_{1c} does not reflect the stability of the glucose level, and fluctuating glucose levels may be more harmful than a constant high level. Continuous glucose monitoring in pregnancy would be valuable in this context, since it would address these issues. Our analysis of maternal episodes of hypoglycemia and ketoacidosis and offspring cognitive function could support this, even though statistical power is limited. Offspring of women with episodes of ketoacidosis obtained very low scores both compared with offspring without maternal ketoacidosis and compared with the normal population mean. Our inability to adjust for confounders is important in this context because educational level and family resources are important confounders in this association. We still think this finding is noteworthy, and

special attention to these children should be considered.

Strengths and Limitations

The major strength to our study was the use of a large well-characterized prospectively followed cohort of women with type 1 diabetes. We had detailed baseline information, enabling us to adjust for multiple confounders and possible mediators in the pathway between maternal diabetes and offspring cognitive function. Unfortunately, we did not have sufficient information about delivery mode, breast-feeding, and maternal smoking in pregnancy to include these variables with possible implications on offspring cognitive function (33). Diverse effects of breast-feeding on cognitive development in offspring of women with diabetes have previously been suggested (34,35).

A limitation is the risk of selection bias, since a limited and different proportion of invited offspring in the two groups agreed to participate at follow-up. This might lead to selection bias if nonparticipation is related to cognitive function. Participation may be associated with parental concern about the child's cognitive function, but nonparticipation is in general associated with lower socioeconomic status, educational level, and health status (36). Cognitive results before standardization and normalization show mean scores in all variables >100 in both groups (data not shown). A mean of 100 is the population mean in intelligence tests and implies that both groups were selected from the better-performing part of the population. Offspring of women with ketoacidosis or hypoglycemia tended to perform worse than offspring of women without these complications, and their participation rate was lower than that for the entire diabetes-exposed group (28% vs. 37%), implying no selection of children with lower performance in the exposed group. The cognitive tests were a minor part of a comprehensive examination plan (9). None of the offspring chose to confine their participation to the cognitive tests, so we do not consider these tests as the primary motivation for participation in either of the groups.

Chronic diseases among the offspring could potentially affect cognitive function, but we did not have sufficient

information to include this in our analyses. Unfortunately, we were not allowed to collect information regarding baseline information in nonparticipants in the control group. In the index group, analysis showed comparability at birth between participants and nonparticipants. There was a slightly better periconceptional HbA_{1c} in the group of mothers with participating index offspring, which probably reflect a higher frequency of pregnancy planning and better glucose control prior to pregnancy. These women tend to have more resources in many aspects of life, and their offspring are not expected to be in the group with the lower cognitive function. An underestimation of the association with exposure is therefore more likely than the opposite. A lower HbA_{1c} could reflect more frequent events of hypoglycemia, but we did not find any difference in hypoglycemic events in early pregnancy between participating and nonparticipating mothers.

We did not have information about maternal or paternal intelligence and were unable to adjust for effects of genetic factors and family environment on offspring cognitive function. Educational achievement and intelligence are considered to be closely related (37,38), and parental educational level is a well-known predictor of offspring cognitive function. Complete adjustment for parental genetic and socioeconomic contribution is difficult, and incomplete adjustment for these factors is the most obvious contributor to residual confounding in our analysis. Individuals with a chronic disease tend to attain a lower educational level compared with those without disease (39), possibly resulting in underadjustment of the genetic contribution in the index group and an underestimation of the association between exposure and outcome—minimized, though, by the inclusion of the paternal educational level.

The missing baseline data in the control group caused by inability to obtain obstetric records could have implications on adjusted analysis. The need for adjustment for multiple comparisons in Table 2 and 3 could be discussed. We considered Bonferroni correction to be too conservative, since outcomes in both tables are closely related and not independent. However, both unadjusted

and most adjusted differences between groups would still be present after Bonferroni correction (data not shown).

In conclusion, results from this well-characterized prospectively followed cohort indicate harmful effects of maternal diabetes on neurodevelopment in the offspring of mothers with type 1 diabetes. Exposure to maternal diabetes had an effect on all intelligence indices, and cues to specific brain areas affected were not obvious in our study. Increased attention to the group of children at special risk of cognitive impairment, who could benefit from early intervention on cognitive difficulties, is necessary. Future studies may be able to evaluate implications of maternal glycemic control in pregnancy using a more precise glycemic measurement.

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