Diabetologia (1996) 39: 1041–1046

Diabetologia

Teratogenic effects of diabetes mellitus in the rat. Prevention by vitamin E

M. Viana[1, 2], **E. Herrera**[2], **B. Bonet**[1, 2]

[1] Hospital del Niño Jesús. Sección de Endocrinología, Madrid, Spain
[2] Facultad de Ciencias Experimentales y Técnicas, Universidad de San Pablo CEU, Madrid, Spain

Summary We wanted to determine whether administration of vitamin E could reduce the production of free radicals which could play a role in the teratogenic effects of diabetes mellitus. Diabetes was induced in Wistar rats by the intravenous administration of streptozotocin. The animals were divided into six groups: one with no supplement (D) and two, supplemented during pregnancy either with oral vitamin E (150 mg/day) (D + E) or with a placebo (safflower oil) (D + O). Three other groups were kept under the same conditions, but were treated with insulin: D + I, D + I + E and D + I + O. There were three groups of matched controls: C, C + E and C + O. All animals were killed on day 11.5 of pregnancy. In C animals the percentages of reabsorptions and malformations were 1.3 and 2 %, respectively, comapred with 23.6, 24.3, 6.2 and 13.2 %, respectively in D and D + I groups. The crown-rump length, number of somites, and protein and DNA content were higher in C animals than in the diabetic rats, independent of insulin treatment. When vitamin E was administered no changes in these parameters were observed in C and D + I animals; however, in the D mothers it reduced the rate of embryo malformations to 4.6 % and increased the crown-rump length and the number of somites. However, vitamin E did not modify the protein and DNA content and the percentage of reabsorptions. In conclusion, administration of vitamin E to diabetic animals decreases the rate of embryo malformations and increases their size and maturation, supporting a role for free radicals in the teratogenic effects of diabetes. [Diabetologia (1996) 39: 1041–1046]

Keywords Diabetes mellitus, teratogenesis, free-radicals, pregnancy, vitamin E.

Poor metabolic control in pre-conception diabetes mellitus is associated with an increased incidence of abortions and congenital malformations [1–4]. Several metabolic parameters, including glucose, ketone bodies and triglycerides, could be involved in the teratogenic effects [5–8]. In the embryo culture model both hyperglycaemia and hyperketonaemia cause embryo malformations [9–11]. Very little is known about the pathophysiological mechanisms involved, which makes any attempt to reduce the rate of embryo malformations, other than by achieving optimal metabolic control, very difficult.

Recently it has been proposed that enhanced production of free radicals could play a role in the teratogenic effects of diabetes [12, 13]. In the embryo culture model, the rate of malformations linked to hyperglycaemia and hyperketonaemia decreases when superoxide dismutase or butylated hydroxitoluene, two free radical scavengers, are added to the culture media [12, 13]. Furthermore, diabetes per se is a state of increased oxidative stress. The concentration of lipid peroxides is increased in cell membranes and lipoproteins of diabetic rats [14, 15]. LDL from pregnant diabetic women is more susceptible to oxidation [16]. Protein glycation, a phenomenon commonly found in diabetes, could generate free radicals [17, 18]. Finally, the concentration of antioxidant vitamins

Received: 15 November 1995 and in final revised form: 2 April 1996

Corresponding author: Dr. B. Bonet, Centro de Ciencias Experimentales y Técnicas, Universidad de San Pablo, CEU, P. O. Box 67, E-28660 Boadilla del Monte (Madrid), Spain

is decreased both in the diabetic experimental animal and in humans [19–21].

Despite these considerations, there are no in vivo studies on the potential benefits of dietary antioxidant treatment for prevention of the teratogenic effects of diabetes. The present study addresses the question whether adding vitamin E, a liposoluble free radical scavenger, to the diet of pregnant diabetic rats could decrease the rate of fetal malformations.

Materials and methods

Animals and experimental design. Female virgin Wistar rats from our own colony, weighing 190–220 g, were housed in a temperature-controlled room (22 ± 1 °C) with alternating 12-h light and dark cycles, and fed a Purina Chow diet (Rat and Mouse Standard diet; Beekay Feeds, B.K: Universal S.L., Barcelona, Spain). The care and handling of the animals throughout the study followed the current animal care law of the European Union.

Diabetes was induced by a single intravenous dose of streptozotocin (45 mg/kg) (Sigma Chemical Co., St. Louis, Mo., USA) in citrate buffer (0.05 mol/l) (pH 4.5). Five days later a state of insulin deficiency was confirmed by a positive reaction of a urine chemistrip for both glucose and ketone bodies, and insulin replacement was started. The insulin dosage was chosen on the basis of our previous laboratory experience [22, 23]; 1.5 IU/100 g body weight of Insulin Lente MC (90 % bovine, 10 % porcine) (Novo Nordisk A/S, Bagsvaerd, Denmark) was injected subcutaneously, between 09.00 and 10.00 hours. The animals were mated and the same day that sperm appeared in vaginal smears (day 0 of gestation) the animals were divided into their experimental groups.

Three groups of diabetic animals, with no insulin administration during pregnancy, one without any supplement (D), another supplemented with 150 mg vitamin E (Alfa-Tocopherol acetate, Sigma) per day, dissolved in safflower oil, total volume 250 µl, administered by gavage from day 1 of pregnancy (D + E) and a third group that received 250 µl safflower oil by gavage (D + O). Three additional groups of diabetic animals were treated with insulin during pregnancy: one with no other supplement (D + I), one receiving the daily vitamin E treatment (D + I + E) and another receiving placebo (safflower oil) (D + I + O), as described above. Finally three groups of normal rats were also studied: an untreated group (C) and two groups supplemented with either vitamin E (C + E) or the placebo.

Rats were decapitated on day 11.5 of gestation, which corresponds to the end of the embryo period. Blood was collected in EDTA (1 mg/ml) and plasma separated and kept at − 20 °C until processed. The two uterine horns were immediately dissected and immersed in a petri dish (100 mm) at room temperature in saline. Embryos and investing membranes were teased apart with fine jewellers forceps during visualization with a dissecting microscope (Carlzeiss Jena 212T OPM, Germany). The yolk sac was isolated from the surrounding decidua and the embryo removed. In all embryos the crown-rump length and the number of somites were determined. All the embryos were inspected to determine whether the morphology of brain spheres, neural tube, heart, optic and otic vesicles, limb buds and axial curvature conformed to that expected on day 11.5 of gestation (Fig. 1). Embryos which did not conform to normal morphology in any of the above structures were considered dysmorphic (Fig. 1). Reabsorptions were considered when the decidua was present but the yolk sac or embryo were not found. After visual inspection, all the embryos were introduced into 0.1 N NaOH and analysed for total protein [24] and DNA [25].

Processing and analysis of the samples. Aliquots of plasma were used to determine glucose (Glucose God-Pad Enzymatic Colorimetric Test; Boehringer Mannheim, Mannheim, Germany), non-esterified fatty acids (NEFA C ACS. Acod Method; Wako Chemicals, Neuss, Germany), triglycerides (Triglycerides Enzymatic Trinder Method; Menarini Diagnostics, Florence, Italy), cholesterol (Cholesterol H.F., Enzymatic Trinder Method, Menarini Diagnostics) and fructosamine (Fructosamine, Hoffmann-La Roche AG, Basel, Switzerland: interassay coefficient of variation 3 %). An aliquot was deproteinized with $Ba(OH)_2$ and $ZnSO_4$ [26] and used for β-hydroxybutyrate determination [27, 28].

Statistical analysis

The mean ± SEM are given. The significance of the difference between the means of two groups was obtained with the analysis of variance and Tuckey test for multiple comparisons, using the Systat program (Systat Inc. Evanston, Ill., USA).

Results

Metabolic parameters. Plasma glucose, β-hydroxybutyrate and fructosamine were measured as an index of the metabolic condition of the animals. As shown in Table 1, plasma concentration of these three parameters was higher in the non-insulin-treated pregnant diabetic rats (D, D + E and D + O) than in any of the control groups (C, C + E and C + O) or the insulin-treated pregnant diabetic rats (D + I, D + I + E and D + I + O) (Table 1). The administration of either vitamin E or the placebo had no effect

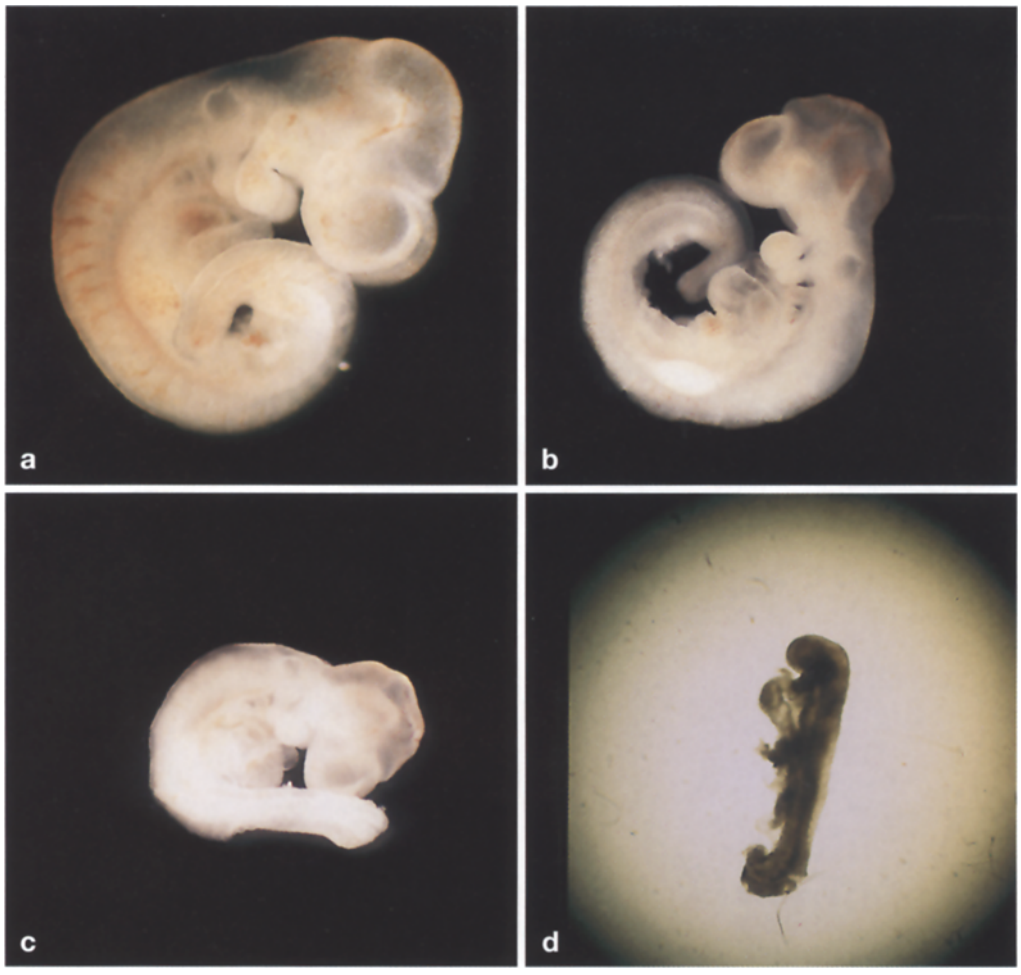

Fig. 1. a–d Rat embryos at day 11.5. **a**) Normal embryo from control animal (× 10). **b, c** and **d**) Malformed embryos from diabetic rats: (**b**) embryo with microcephaly (× 10); (**c**) Small embryo with severely malformed head and posterior neural pore open (× 10); (**d**): Severely malformed embryo (× 16)

on the plasma levels of glucose, β-hydroxybutyrate or fructosamine in either the control or diabetic groups not receiving insulin treatment (Table 1). Although insulin treatment reduced plasma glucose levels in the three diabetic groups, the effect was higher in rats receiving either vitamin E or placebo treatment, which attained levels that did not differ from their respective control groups. However, neither plasma β-hydroxybutyrate nor fructosamine levels differed between any of the diabetic groups receiving insulin treatment and their respective control groups (Table 1). However, although the NEFA concentration did not differ between D + I and control rats, it was lower in D + I + E and D + I + O rats (Table 1).

The concentration of plasma triglycerides and cholesterol was similar in all the experimental groups studied, both diabetic and controls (Table 1). Only the D + O group showed levels of triglycerides higher than those in the remaining groups (Table 1), suggesting that the administration of safflower oil could increase the plasma triglycerides, although this effect was only observed in this group. The administration of vitamin E had no effect on either parameter (Table 1).

Analysis of embryos. The embryos of D rats had a shorter crown-rump length, and lower number of somites and DNA and protein concentration than both C and D + I embryos ($p < 0.001$) (Table 2). In pregnant diabetic rats insulin treatment increased the crown-rump length, the number of somites and the DNA and protein content, although these did not reach the values observed in embryos of control animals (Table 2).

In diabetic rats vitamin E administration (D + E) increased the crown-rump length and the number of somites to values which were statistically higher than those of D embryos ($p < 0.01$), and reaching values similar to those of D + I embryos (Table 2), although still lower than those of the control animals (Table 2). No effects were observed in the protein and DNA content of D + E embryos compared to D embryos (Table 2).

The administration of placebo to D rats (D + O) had no effect on the crown-rump length or the number of somites but decreased both the embryo protein and DNA content when compared to D embryos ($p < 0.001$) (Table 2). A similar finding was observed in the embryos of insulin-treated diabetic rats when placebo was administered (D + I + O), as

Table 1. Metabolic parameters in diabetic rats. Effects of insulin, vitamin E and placebo

Group	Number of rats (*n*)	Glucose (mmol/l)	β-OH-Butyrate (μmol/l)	NEFA (μmol/l)	Fructosamine (mmol/l)	Triglycerides (mmol/l)	Cholesterol (mmol/l)
C	12	6.5 ± 0.2	133.5 ± 25	574.4 ± 53	174.4 ± 3	1.7 ± 0.1	1.6 ± 0.07
C + E	7	6.3 ± 0.3	191.3 ± 46	609.6 ± 87	176.7 ± 9	2.2 ± 0.3	1.7 ± 0.11
C + O	7	6.7 ± 0.3	141.9 ± 22	575.7 ± 64	180.6 ± 12	1.2 ± 0.1	1.6 ± 0.11
D	11	27.8 ± 3.8^{a,z}	284.1 ± 54	568.4 ± 49	277.0 ± 31^{c}	2.6 ± 0.5	1.8 ± 0.12
D + E	9	24.4 ± 4.1^{a,x}	355.3 ± 98^{z}	522.1 ± 51^{z}	274.8 ± 27^{b,z}	1.6 ± 0.1	1.4 ± 0.08
D + O	7	32.8 ± 2.5^{a,x}	327.0 ± 61	698.4 ± 73^{x}	291.6 ± 10^{b,z}	3.7 ± 1.2^{b,x,r}	1.8 ± 0.18
D + I	14	18.0 ± 2.2^{b}	136.1 ± 35	441.3 ± 27	230.2 ± 28	2.2 ± 0.2	1.7 ± 0.09
D + I + E	9	8.3 ± 0.8	99.3 ± 27	269.2 ± 35^{a}	182.0 ± 6	1.5 ± 0.3	1.6 ± 0.09
D + I + O	11	8.6 ± 1.4	182.1 ± 40	286.2 ± 17^{b}	198.4 ± 14	1.2 ± 0.1	1.6 ± 0.07

Control, diabetic and insulin-treated diabetic animals, with no supplementation (C, D and D + I), supplemented with vitamin E (C + E, D + E and D + E + I) or with placebo (safflower oil) (C + O, D + O and D + I + O). Differences between diabetic rats, treated or not with insulin vs control animals, given the same supplement (vitamin E or placebo) $^{a}p < 0.001$; $^{b}p < 0.01$; $^{c}p < 0.05$. Differences between diabetic rats treated with insulin vs those not treated, given the same supplement (vitamin E or placebo) $^{x}p < 0.001$; $^{y}p < 0.01$; $^{z}p < 0.05$. Differences between animals of the same experimental group (control, diabetic and insulin-treated diabetic animals) with no supplement vs rats given vitamin E or placebo; $^{m}p < 0.001$; $^{n}p < 0.01$; $^{r}p < 0.05$

Table 2. Number of somites, crown-rump length, total protein and total DNA content in 11.5-day-old rat embryos

Group	Embryos (*n*)	Somites (*n*)	Crown-rump (mm)	Protein (μg)	DNA (μg)
C	148	29.4 ± 0.1	4.1 ± 0.03	334.4 ± 8.1	134.7 ± 8.3
C + E	104	29.9 ± 0.1	4.2 ± 0.03	348.6 ± 4.5	108.5 ± 3.6
C + O	88	29.4 ± 0.2	4.3 ± 0.03	348.6 ± 6.5	104.2 ± 3.1
D	107	27.7 ± 0.3^{a,x}	3.7 ± 0.06^{a,z}	309.7 ± 13.9	107.5 ± 7.8^{y}
D + E	82	28.8 ± 0.5^{a,n}	3.8 ± 0.05^{a,n}	298.6 ± 8.8^{b}	96.2 ± 3.7
D + O	35	27.4 ± 0.5^{a}	3.6 ± 0.08^{a}	229.7 ± 10.7^{a,m}	66.2 ± 4.9
D + I	167	28.6 ± 0.1^{c}	3.9 ± 0.03^{c}	340.7 ± 11.4	141.0 ± 13.1
D + I + E	118	28.8 ± 0.2^{b}	4.0 ± 0.04^{a}	289.9 ± 9.1^{a}	94.4 ± 2.8
D + I + O	133	28.4 ± 0.2^{b}	3.9 ± 0.07^{b}	282.1 ± 6.5^{c}	88.4 ± 3.0

Control, diabetic and insulin-treated diabetic animals, with no supplementation (C, D and D + I), supplemented with vitamin E (C + E, D + E and D + E + I) or with placebo (safflower oil) (C + O, D + O and D + I + O). Differences between diabetic rats, treated or not with insulin vs control animals, given the same supplement (vitamin E or placebo) $^{a}p < 0.001$; $^{b}p < 0.01$; $^{c}p < 0.05$. Differences between diabetic rats treated with insulin vs those not treated, given the same supplement (vitamin E or placebo) $^{x}p < 0.001$; $^{y}p < 0.01$; $^{z}p < 0.05$. Differences between animals of the same experimental group (control, diabetic and insulin-treated diabetic animals) with no supplement vs rats given vitamin E or placebo; $^{m}p < 0.001$; $^{n}p < 0.01$; $^{r}p < 0.05$

compared to those receiving no other treatment (D + I).

The incidence of reabsorptions and malformations was respectively 1.3 and 2 % in the control group (C) (Table 3). In the D group the rate of reabsorptions and malformations increased to 23.6 and 24.3 %, respectively. Administration of insulin to diabetic rats (D + I) decreased the incidence of reabsorptions to 6.2 % and of malformations to 13.2 %.

In D animals, vitamin E administration from day 1 of pregnancy had no effect on the incidence of reabsorptions (30.1 % in D + E vs 23.6 % in D rats), but drastically decreased the number of malformations in embryos of the D group from 24.3 to 4.6 % (Table 3). However, vitamin E administration had no effect on the rate of reabsorptions and malformations in control or insulin-treated pregnant diabetic rats (Table 3).

The administration of placebo (safflower oil) had a negative effect in C animals, where an increase in malformations (2 % in C vs 5.7 % in C + O) and reabsorptions (1.3 % in C vs 6.4 % in C + O) was observed. A similar effect was found in diabetic animals where the administration of safflower oil (D + O) increased the rate of malformations and reabsorptions to 48.6 and 56.8 %, respectively from 24.3 and 23.6 % in D animals (Table 3). No changes were observed in insulin treated pregnant diabetic rats when given with placebo (Table 3).

Discussion

In rats from our colony, as would be expected, poorly controlled diabetes is highly teratogenic. Fifty percent of the embryos are affected when considering malformations (24.3 %) and reabsorptions (23.6 %). The rate of embryo malformations in diabetic rats varies widely among different colonies [29]. Our colony therefore offers an excellent model with which to study the teratogenic effects of diabetes in vivo.

Table 3. Rate of malformations and reabsorptions

Group	Yolk sacs	Yolk sac with reabsortions		Embryos		
				Total	Malformed	
	n	*n*	(%)	*n*	*n*	(%)
C	150	2	(1.3)	148	3	(2.0)
C + E	104	0	(0)	104	2	(1.9)
C + O	94	6	(6.4)	88	5	(5.7)
D	140	33	(23.6)	107	26	(24.3)
D + E	119	37	(30.1)	82	4	(4.6)
D + O	81	46	(56.8)	35	17	(48.6)
D + I	178	11	(6.2)	167	22	(13.2)
D + I + E	130	12	(7.8)	118	18	(15.2)
D + I + O	145	12	(8.3)	133	21	(15.8)

The embryos were studied as described in the methods section. Control, diabetic and insulin-treated diabetic animals, with no supplementation (C, D and D + I), supplemented with vitamin E (C + E, D + E and D + E + I) or with placebo (safflower oil) (C + O, D + O and D + I + O)

In diabetic rats, oral administration of vitamin E, from day 1 of pregnancy, decreased the rate of embryo malformations from 24.3 to 4.6 %. These results demonstrate that in the experimental animal, vitamin E administration early in pregnancy reduces the incidence of embryo malformations secondary to diabetes. It remains to be determined whether vitamin E could have similar effects on human diabetic pregnancies, where the incidence of embryo malformations is still two- to threefold higher than in non-diabetic pregnancies, particularly when optimal metabolic control is not achieved [1–3].

Our results in vivo are in agreement with the findings in the embryo culture model, where the rate of malformations induced by high glucose and ketone body concentrations decreased when free radical scavengers, superoxide dismutase or butylated hydroxytoluene, were added to the media [12, 13]. All of these findings support the hypothesis of free radical-mediated teratogenesis.

The number of reabsorptions did not decrease in diabetic rats treated with vitamin E, which suggests that the damage produced by diabetes in the early phase of development was not reversed by this treatment. This agrees with the reported finding that diabetes can have negative effects on blastocyst development, decreasing the number of inner cells [30, 31], which are precursors of the embryo, and these effects are not reversible [30]. Furthermore, it cannot be ruled out that some components of diabetic embryopathy, leading to embryo reabsorptions, are not mediated by free radicals, and therefore are not suitable for targeting with antioxidants.

Administration of insulin to diabetic rats before and during pregnancy was found to decrease the rate of reabsorptions and embryo malformations to one-half the values observed in non-treated diabetic rats; however, incidence was still higher than in the control group. This took place despite achieving good metabolic control, as indicated by a decreased plasma glucose, and NEFA, β-hydroxybutyrate and fructosamine levels which were smilar to values observed in the control animals. Short periods of hypo- or hyperglycaemia could have occurred during the 24-h period between insulin administrations and they could have been responsible for the elevated number of reabsorptions and malformations observed in the D + I groups, since it has been shown that short periods of hypo- or hyperglycaemia may be teratogenic when occurring during critical periods of embryo development [32, 33]. Also, other teratogenic effects secondary to diabetes may not involve free radical generation or even be directly related to glucose or hydroxybutyrate. In fact, other authors have shown that in the embryo culture model plasma from diabetic rats remains teratogenic, despite normalization of plasma glucose and ketone bodies [10].

Administration of safflower oil as placebo increased the rate of malformations and reabsorptions in both normal and diabetic pregnancies. Fatty acids, especially polyunsaturated, are rapidly oxidized in pro-oxidative situations [34], such as the diabetic environment. Therefore, it is possible that administration of oil increased the generation of free radicals, leading to embryo malformations.

In summary, we have shown that oral administration of vitamin E, to diabetic rats from day 1 of pregnancy has no effect on the rate of embryo reabsorptions but decreases the high incidence of embryo malformations. To our knowledge these are the first results which demonstrate, in vivo, the protective effects of a dietary antioxidant on the teratogenic effects of diabetes, despite the fact that vitamin E treatment did not improve metabolic control in the rats studied. Clinical trials where vitamin E is administered either before or in early pregnancy are needed in order to demonstrate similar effects in human diabetic pregnancies.

Acknowledgements. The authors wish to acknowledge Ms. R. Niño for secretarial support. This work was supported by a Grant from the Ministerio de Educacion (DGICYT, PB92-0833) and the Ministerio de Salud (FIS 94-0398).

References

1. Lucas MJ, Leveno KJ, Williams ML, Raskin P, Whalley PJ (1989) Early pregnancy glycosylated hemoglobin, severity of diabetes, and fetal malformations. Am J Obstet Gynecol 161: 426–431
2. Mills JL, Knopp RH, Simpson JL et al. (1988) Lack of relation of increased malformation rates in infants of diabetic mothers to glycemic control during organogenesis. N Engl J Med 318: 671–676
3. Miller E, Hare JW, Cloherty JP et al. (1981) Elevated maternal hemoglobin a in early pregnancy and major congenital anomalies in infants of diabetic mothers. N Engl J Med 304: 1331–1334

4. Mills JL, Simpson JL, Driscoll SG et al. (1988) Incidence of spontaneous abortion among normal women and insulin-dependent diabetic women whose pregnancies were identified within 21 days of conception. N Engl J Med 319: 1617–1622
5. Freinkel N (1980) Banting lecture 1980. Of pregnancy and progeny. Diabetes 29: 1023–1035
6. Eriksson UJ, Borg LAH, Forsberg H, Styrud J (1991) Diabetic embryopathy. Studies with animal and in vitro models. Diabetes 40: 94–97
7. Freinkel N (1988) Diabetic embryopathy and fuel-mediated organ teratogenesis: lessons from animal models. Horm Metab Res 20: 463–475
8. Eriksson RSM, Thunberg L, Eriksson UJ (1989) Effects of interrupted insulin treatment on fetal outcome of pregnant diabetic rats. Diabetes 38: 764–772
9. Horton WE, Sadler TW (1983) Effects of maternal diabetes on early embryogenesis. Alterations in morphogenesis produced by the ketone body, *B*-hydroxybutyrate. Diabetes 32: 610–616
10. Buchanan TA, Denno KM, Sipos GF, Sadler TW (1994) Diabetic teratogenesis: in vitro evidence for a multifactorial etiology with little contribution from glucose per se. Diabetes 43: 656–660
11. Eriksson UJ, Karlsson M, Styrud J (1987) Mechanisms of congenital malformations in diabetic pregnancy. Biol Neonate 51: 113–118
12. Eriksson UJ, Borg LAH (1991) Protection by free oxygen radical scavenging enzymes against glucose-induced embryonic malformations in vitro. Diabetologia 34: 325–331
13. Eriksson UJ, Borg LAH, Forsberg H, Simán MC, Suzuki N, Yang X (1995) Advances in the understanding of diabetic embryopathy: antioxidant mechanisms. 2nd Inter Symp Diabetes and Pregnancy in the 90's. Jerusalem, Israel (Abstract)
14. Jain SK, Levine SN, Duett J, Hollier B (1990) Elevated lipid peroxidation levels in red blood cells of streptozotocin-treated diabetic rats. Metabolism 39: 971–975
15. Morel DW, Chisolm GM (1989) Antioxidant treatment of diabetic rats inhibits lipoprotein oxidation and cytotoxicity. J Lipid Res 30: 1827–1834
16. Bonet B, Knopp RH (1992) Accelerated LDL oxidation in diabetic gestation. 2nd Internat Graz Symp on Gestational Diabetes (Abstract)
17. Mullarkey CJ, Edelstein D, Brownlee M (1990) Free radical generation by early glycation products: a mechanism for accelerated atherogenesis in diabetes. Biochem Biophys Res Commun 173: 932–939
18. Hunt JV, Smith CCT, Wolff SP (1990) Autooxidative glycosylation and possible involvement of peroxides and free radicals in LDL modification by glucose. Diabetes 39: 1420–1424
19. Jain SK, Levine SN, Duett J, Hollier B (1991) Reduced vitamin E and increased lipofuscin products in erythrocytes of diabetic rats. Diabetes 40: 1241–1244
20. Cunningham JJ, Ellis SL, McVeigh KL, Levine RE, Calles-Escandon J (1991) Reduced mononuclear leukocyte ascorbic acid content in adults with insulin-dependent diabetes mellitus consuming adequate dietary vitamin C. Metabolism 40: 146–149
21. Tsai EC, Hirsch IB, Brunzell JD, Chait A (1994) Reduced plasma peroxyl radical trapping capacity and increased susceptibility of LDL to oxidation in poorly controlled IDDM. Diabetes 43: 1010–1014
22. Martín A, Herrera E (1991) Different responses to maternal diabetes during the first and second half of gestation in the streptozotocin-treated rat. Isr J Med Sci 27: 442–448
23. Martín A, Ramos P, Herrera E (1993) Modulation of lipoprotein lipase activity in adipose tissue during late pregnancy. In: Medina JM, Quero J (eds) Physiologic basis of perinatal care. Ediciones Ergon, Madrid, pp 117–122
24. Lowry OH, Rosebrough NJ, Farr AL et al. (1951) Protein measurement with the Folin phenol reagent. J Biol Chem 193: 265–275
25. Hinegardner RT (1971) An improved fluorometric assay for DNA. Anal Biochemistry 39: 107–201
26. Somogyi M (1945) Determination of blood sugar. J Biol Chem 160: 69–73
27. Bonet B, Herrera E (1991) Maternal hypothyroidism during the first half of gestation compromises normal catabolic adaptations of late gestation in the rat. Endocrinology 129: 210–216
28. Williamson DH, Mellanby T, Krebs HA (1962) A enzymatic determination of D-β-hydroxybutiric acid and acetonic acid in blood. Biochem J 82: 90–96
29. Otani H, Tanaka O, Tatewaki R, Naora H, Yoneyama T (1991) Diabetic environment and genetic predisposition as causes of congenital malformations in NOD mouse embryos. Diabetes 40: 1245–1250
30. Pampfer S, Wuu YD, Vanderheyden I, De Hertogh R (1994) In vitro study of the carry-over effect associated with early diabetic embryopathy in the rat. Diabetologia 37: 855–862
31. Diamond MP, Harbert-Moley K, Logan J et al. (1990) Manifestation of diabetes mellitus on mouse follicular and preembryo development: effect of hyperglycemia per se. Metabolism 39: 220–224
32. Tanigawa K, Kawaguchi M, Tanaka O, Kato Y (1991) Skeletal malformations in rat offspring. Long-term effect of maternal insulin-induced hypoglycemia during organogenesis. Diabetes 40: 1115–1121
33. Buchanan TA, Schemmer JK, Freinkel N (1986) Embryotoxic effects of brief maternal insulin-hypoglycemia during organogenesis in the rat. J Clin Invest 78: 643–649
34. Esterbauer H, Gebicki J, Puhl H, Jürgens G (1992) The role of lipid peroxidation and antioxidants in oxidative modification of LDL. Free Rad Biol Med 13: 341–390