Blood Sugar Levels and Renal Sugar Excretion After the Intake of High Carbohydrate Diets in Cats[1,2]

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ABSTRACT The effect of starch and sugars on blood sugar level and renal excretion of sugars and galactitol was investigated. Fifty-nine adult cats were divided into seven dietary groups (carbohydrate content in dry matter): STARCH (29–37% starch, decomposed or raw), SUC (36% sucrose), LAC1 and LAC2 (11 and 28% lactose, respectively), GLUC (40% glucose), GAL (39% galactose) and a carbohydrate-free control diet, FAT. Diet STARCH did not significantly influence postprandial blood glucose level (3.65 ± 0.68 mmol/l ± SD, n = 16) compared with diet FAT (3.20 ± 0.77 mmol/l, n = 14) 1, 3 or 6 h after feeding (weighted means). Diet GLUC led to a steep rise in blood glucose concentration 1 h after feeding (5.08 ± 0.69 mmol/l, n = 6). Diet SUC induced a mild persistent hyperglycemia without marked postprandial changes (4.52 ± 0.52 mmol/l, n = 15, weighted mean of 0, 3 and 6 h postprandially). Diet GAL induced persistent hypoglycemia before and after feeding (2.58 ± 0.38 mmol/l, n = 13) and considerable postprandial galactosemia (3.26 ± 1.38 mmol/l, n = 7). In the groups STARCH and FAT, glucose was only detectable in traces in urine, whereas all diets containing sugars led to glucosuria. In group SUC, fructose and sucrose were found in urine and in both lactose groups galactose and lactose were found. Diet GAL led to galactosuria (140 mmol galactose/l). In group LAC1, and especially in group GAL, galactitol was detected in urine. These results point to a rather limited capacity of the cat to metabolize sugars. J. Nutr. 124: 2563S–2567S, 1994.

INDEXING KEY WORDS:

• *cat* • *carbohydrate* • *blood sugar concentration* • *renal sugar excretion*

The strictly carnivorous cat shows several peculiarities of protein and fat metabolism (Rogers and Morris 1991). Several observations indicate that the cat is not very well equipped to metabolilze carbohydrates, especially sugars. For example, the respiratory quotient does not increase to the same degree after refeeding of sugars to fasted cats as it does in other species (Carpenter 1944), the cat does not possess glucokinase in the liver (Ballard 1965) and glucose elimination time after intravenous or oral glucose tolerance tests is elongated in the cat compared with other species (Brieger 1984, Kienzle 1989, Mansfield et al. 1986). In this investigation high carbohydrate diets were fed to adult cats and blood levels and urinary excretion of various sugars were determined.

MATERIALS AND METHODS

Fifty-nine adult cats were used for the investigation [3.6 ± 1.1 kg body weight (means ± standard deviation), range from 1.6 to 6.4 kg, aged 1–5 years, females and neutered and intact males]. The cats were divided into nine dietary groups (**Table 1**) with at least three cats per group. However, as no significant difference in any of the parameters was observed in the three groups fed different starch diets, the results from these groups were combined to form the STARCH group. The cats were adapted to their diets for ≥3 wk before samples were taken.

During the first part of the experiment, the cats had free access to their food. They were kept in cages allowing a separate collection of urine and feces. Urine was collected over a 24-h period. In the second part of the experiment, the cats were meal fed after 12 h of fasting. Blood samples (cephalic vein) were taken before feeding and at 1, 3 and 6 h after the meal. Na-Heparinate was added to all samples, and then they were immediately deproteinized as follows. For glucose, galactose and lactose determination $HClO_4$ (0.6 mol/l) was added to the blood, and for sucrose and

[1] Presented as part of the Waltham Symposium on the Nutrition of Companion Animals in association with the 15th International Congress of Nutrition, at Adelaide, SA, Australia, on September 23–25, 1993. Guest editors for this symposium were Kay Earle, John Mercer and D'Ann Finley.

[2] Supported by Deutsche Forschungsgemeinschaft.

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TABLE 1

***Diets and diet groups*[1]**

	STARCH1	STARCH2	STARCH3	SUC	GLUC	GAL	LAC1	LAC2	FAT
					g/kg diet				
Dry matter	438	416	230	489	465	471	440	474	442
Carbohydrates					*g/kg dry matter*				
Raw potato starch	372	—	—	—	—	—	—	—	—
Raw maize starch	—	345	—	—	—	—	—	—	—
Cooked maize starch	—	—	286	—	—	—	—	—	—
Sucrose	—	—	—	361	—	—	—	—	—
Glucose	—	—	—	—	398	—	—	—	—
Galactose	—	—	—	—	—	388	—	—	—
Lactose	—	—	—	—	—	—	113	280	—
Crude nutrients and minerals									
Crude protein	330	316	439	294	351	375	447	377	408
Crude fat	177	184	156	144	189	155	220	188	433
Ca	19.6	19.3	22.3	17.4	20.6	27.0	33.1	23.3	23.3
P	11.0	10.7	14.0	11.2	10.5	14.9	18.8	12.9	11.9
Mg	0.7	0.7	0.7	0.6	0.7	0.8	1.0	0.8	0.7
Na	1.8	2.0	4.6	1.8	1.6	1.7	2.3	1.8	1.8
					$g \cdot kg^{-1}$ *body weight* $\cdot d^{-1}$				
Carbohydrate intake[2]	8.9	8.8	4.7	7.2	5.1	5.6	1.3	4.5	0

[1] Carbohydrate-free ingredients: meat meal, poultry meal, fish meal, bone meal, egg yolk, fish oil, lard and water. Vitamin supplementation per kg air-dry matter: 100 mg vitamin E premix (50% α-tocopherol) and 10 g vitamin mixture. Composition of vitamin mixture per kg: 600 mg vit. A, 12.5 mg vit. D-3, 5200 mg α-tocopheryl-acetate, 20,000 mg Na-ascorbate, 1500 mg vit. B-1, 2000 mg vit. B-2-5-phosphate-sodium, 2000 mg vit. B-6, 20 mg vit. B-12-cyanocomplex, 20,000 mg nicotinamide, 6500 mg Ca-pantothenate, 400 mg folic acid, 3000 mg menadione-Na-bisulfite; trace element content per kg dry matter: Fe 140-240 mg. Cu 14-36 mg, Zn 70-100 mg, Mn 9-15 mg.

[2] Does not include carbohydrate in vitamin mixture that was common to all diets and <1% of the diet by weight.

fructose determination $Ba(OH)_2$ (0.29 mol/l) and $ZnSO_4$ (0.28 mol/l, solutions in distilled water) were used with plasma. Glucose in blood was analyzed with glucose oxidase, peroxidase and 2,2'azino-di-(3-ethyl-benzthiazolon)-6'sulfate, glucose in urine with ATP, hexokinase, glucose-6-phosphate-dehydrogenase and NADP (test kits from Boehringer, Mannheim, Germany). Sucrose was determined with the glucose-6-phosphate-dehydrogenase method after liberation of glucose by β-fructosidase. Fructose was phosphorylated (hexokinase, ATP) and transformed to glucose by fructose isomerase. Glucose was finally determined with glucose 6-phosphate-dehydrogenase. Galactose determination was carried out with galactose-dehydrogenase and NAD, lactose by galactose determination as described above after cleavage of lactose by β-galactosidase. Methods are described in detail by Bergmeyer (1985).

For thin-layer chromatography of urine samples, silica gel-plates (HPTCL, Merck, Germany) were used. The eluate was 1-butanole, 2-propanole, concentrated acetic acid and 0.5% boric acid (37 + 63 + 2.5 + 12 parts, respectively). The plates were incubated twice for 8 h in the chambers. They were air dried after each incubation. The plates were stained with 4-methoxybenzaldehyde spray (0.5 ml 4-methoxybenzaldehyde in 50 ml concentrated acetic acid with 1 ml concentrated sulphuric acid) for the detection of sugars and with $KMnO_4$ (0.5 g in 100 ml NaOH, 1 mol/l) spray for sugar alcohols (Stahl 1967).

For statistical analysis, means and standard deviation were calculated. Multiple comparisons were carried out by one-way analysis of variance and Tukey test. In tables the least significant difference is given that characterizes the minimal difference between two means differing significantly ($P < 0.05$).

RESULTS

Blood sugar levels. No postprandial changes in blood glucose concentration occurred after the consumption of either the carbohydrate-free (FAT) or the STARCH diets. Diet GLUC induced a large significant increase within 1 h. Diet LAC1 had no significant effect on blood glucose level 3 h after feeding compared with baseline values. In group SUC there were no significant changes after feeding, but compared with most other groups (exceptions see **Table 2**) diet SUC led to

TABLE 2

***Blood glucose concentration*[1]**

Diet group	Before feeding	1 h after feeding	3 h after feeding[2]	6 h after feeding	Least significant difference[3]
			mmol/l		
FAT	3.31 ± 0.43 (5)	3.18 ± 0.29 (7)	2.94 ± 0.83 (5)	3.92 ± 1.76 (2)	1.43
STARCH	4.15 ± 0.57 (15)	3.76 ± 0.39 (5)	3.22 ± 1.11 (4)	3.89 ± 0.69 (7)	1.00
GLUC	3.59 ± 0.59 (6)	5.08 ± 0.69 (6)	3.94 ± 0.79 (6)	3.63 ± 0.97 (6)	1.25
SUC	4.31 ± 0.56 (7)	—	4.77 ± 0.47 (5)	4.62 ± 0.39 (3)	0.91
GAL	2.63 ± 0.40 (7)	2.53 ± 0.38 (6)	—	—	0.48
LAC1	3.40 ± 0.23 (5)	—	3.35 ± 0.49 (5)	—	0.56
LAC2	—	—	—	4.14 ± 0.62 (3)	—
Least significant difference[3]	0.85	0.75	1.44	2.01	

[1] Values are means ± standard deviation; number of samples is in parentheses.

[2] Preliminary experiments with sucrose indicated a rather small increase of blood glucose in the first hour after application and a peak glucose concentration after 3 h; therefore, in group SUC and LAC1 the first blood samples were drawn at this point. LAC2 was not completely investigated for technical reasons.

[3] Least significant difference was calculated by Tukey test after one-way analysis of variance; it characterizes the minimal difference between two means (in the same row or column, respectively) differing significantly ($P < 0.05$).

a mild hyperglycemia. Diet GAL on the other hand led to hypoglycemia compared with most other groups. Small amounts of fructose (0.23 + 0.16 mmol/l, n = 12) were observed postprandially (3 h) in the blood in group SUC. In both lactose groups galactose was not detectable in the blood. The GAL diet induced postprandial (1 h) galactosemia (3.26 ± 1.38 mmol/l, n = 7) higher than blood glucose in this group.

Sugars in urine. Only traces of glucose were detectable in the urine of cats fed the FAT or STARCH diets, but in all groups consuming sugar-containing diets glucosuria occurred (**Table 3**). This was particularly so for the monosaccharide diets GLUC and GAL. Fructose occurred in the urine from group SUC and galactose in the urine from the groups LAC1 and LAC2 as well as GAL. In the latter group, galactosuria was most prominent. All disaccharide diets (SUC, LAC1 and LAC2) led to the excretion of the respective disaccharide in the urine (Table 3). In cats fed either diet LAC1 or GAL, galactitol was detectable in the urine. Traces of sorbitol were also apparent on the chromatographic plates in urine from cats fed the GLUC and SUC diets[4]. One of the cats in group GAL developed a cataract on each eye during the experiment, but it disappeared within a few months after the cat was fed a normal commercial pet food. In one of the cats that had been on the SUC diet, histological alterations in the kidney were observed. These in-

[4] This was an accidental finding when urine samples from cats fed GLUC, SUC or FAT were used as controls compared with GAL for the analysis of galactitol.

TABLE 3

***Concentration of sugars and galactitol in urine*[1]**

Diet group	Glucose	Fructose	Sucrose	Galactose	Lactose	Galactitol
			(mmol/l)			
FAT	Traces	ND[2]	ND	ND	ND	ND
STARCH	Traces	—	—	—	—	ND
GLUC	1.58 ± 1.95 (12)	—	—	—	—	ND
SUC	0.45 ± 0.23 (4)	11.4 ± 14.3 (8)	3.40 ± 2.33 (8)	—	—	ND
GAL	3.31 ± 2.18 (15)	—	—	140.2 ± 42.9 (12)	—	++
LAC1	0.26 ± 0.12 (11)	—	—	1.36 ± 1.93 (11)	2.71 ± 1.57 (11)	+
LAC2	0.32 ± 0.33 (5)	—	—	0.24 ± 0.33 (5)	5.03 ± 4.52 (5)	ND

[1] Values are means ± standard deviation; number of samples in parentheses. +, small spots on chromatogram; ++, big spots on chromatogram. If spot size is compared with those of sugars with known concentrations, a galactitol concentration of between 0.2 and 5 mmol/l (for smallest and biggest spots, respectively) can be estimated.

[2] ND, not detectable.

cluded fatty degeneration of tubular cells with periodic acid Schiff-(PAS)-positive material in degenerated cells, reabsorption of PAS-positive material and hyalinosis of glomerular loops.

The GAL diet increased urine volume (GAL 29.1 ± 11.2 ml·kg^{-1} body weight·d^{-1}, n = 4) compared with the GLUC 13.6 ± 1.8 ml·kg^{-1} body weight·d^{-1}, n = 6) and the carbohydrate-free control (FAT 18.8 ± 2.9 ml·kg^{-1} body weight·d^{-1}, n = 6).[5] Urine pH increased signficantly in group LAC1 (7.16 ± 0.76, n = 15 samples) and GAL (8.26 ± 0.78, n = 8) but not in group LAC2 (6.39 ± 0.45, n = 6) compared with cats fed all other diets (6.44 ± 0.13, n = 31). In the groups LAC2 and SUC, acid osmotic diarrhea was observed.

DISCUSSION

It is clear that the cat is not very equipped to metabolize large amounts of sugars. Intravenous sugar tolerance of cats has been shown to be smaller than in dogs or humans by various authors (glucose: Brieger 1984, Kenzle 1989, Lautt 1984, Mansfield et al. 1986, O'Brien et al. 1985; fructose and galactose: Kienzle 1989).

The blood and urine fructose levels after the intake of sucrose, a disaccharide that is incompletely digested by intestinal sucrase (diarrhea was observed in this group, indicating incomplete digestion, and a low sucrase activity has been shown for cats) (Kienzle 1993a,b), point to a slow metabolism of fructose. It is tempting to speculate that not only glucokinase but also fructokinase is lacking in the cat (J. G. Morris, personal communication).

The appearance of galactitol in urine in the groups LAC1 and GAL indicates that galactose has been metabolized via the aldose-reductase pathway because the capacity of the UDP-galactosyl-transferase pathway is exceeded, as seen in humans with enzyme defects (Karlson et al. 1982). The toxic effects of galactose in such individuals as well as in adult galactose-fed animals eating large amounts of galactose is thought to be at least partly due to the accumulation of galactose-1-phosphate. Galactose-1-phosphate inhibits several enzymes of carbohydrate metabolism, among which is glucose-6-phosphatase (Shreeve 1974).

The cataract observed in one galactose-fed cat is probably due to osmotic effects of sugar alcohol in the lens (Kinoshita et al. 1962). This theory appears especially probable because it was reversible. The increase in urine volume in cats fed diet GAL is probably due to osmotic effects of large amounts of sugars in the urine. The increase of urine pH in cats fed diet LAC1 and GAL may be partly due to disorders of renal energy metabolism and/or to interference with the reabsorption of amino acids from the renal tubuli (Fischer and Weinland 1965). The toxicity of galactose is not a peculiarity of the cat but has been observed in several other species (Fischer and Weinland 1965).

Although galactose has been shown to be toxic in several other species (Fischer and Weinland 1965), the signs of toxicity in these cats were observed at a relatively low intake of galactose (5.6 g·kg^{-1} body weight·d^{-1}) compared to 8 g/kg in the rats used by Van Heyningen (1959). Furthermore, galactitol was found in the urine from cats fed diet LAC1 (1.3 g lactose·kg^{-1} body weight·d^{-1}). Even if all the lactose were digested and the monosaccharides absorbed from the small intestine, the galactose absorption would not exceed 0.6 g/kg body weight. This indicates that small doses of galactose can induce alterations of metabolism. At first glance it appears confusing that in diet LAC2 with the higher lactose dose no galactitol was found in urine and also that galactose concentration was lower than in group LAC1. This is probably a result of the intestinal effects of lactose. In contrast to diet LAC2, diet LAC1 did not lead to diarrhea (Kienzle 1993a). It is likely that due to osmotic effects passage time through the small intestine was much lower in group LAC2 than in group LAC1, thus allowing less time for the cleavage of lactose by the rather low intestinal lactase activity of the cat (Kienzle 1993b).

The results on all three monosaccharides tested show that they are not a good component for diets and—more important—for clinical use in enteral or parenteral nutrition.

Because cats have low activity of sucrase and lactase in the small intestinal mucosa (Kienzle 1993b), the occurrence of disaccharides in the urine of the SUC-, LAC1- and LAC2-fed cats was not surprising as it is considered in the humans to be a sign of disaccharidase deficiency (Marks and Samols 1968). The appearance of disaccharides in the urine of dogs fed disaccharide-containing diets has been described by Bennet and Coon (1966) and Mühlum et al. (1989). Disaccharides that escape digestion in the small intestine can be absorbed from the large bowel. Disaccharides appear in urine after rectal infusion of disaccharide solutions in cats (Kienzle 1989). Humans and rats do not metabolize sucrose (Weser and Sleisenger 1967), and there is minimal catabolism of lactose in rats (Carleton and Roberts 1959). This is also the case in the cat as has been shown by the recovery of disaccharides in the urine after intravenous infusion of disaccharide solutions (Kienzle 1989). Renal excretion of disaccharides may be of practical importance. It is not possible to estimate the risk of renal damage from one single report on histological alterations in the kidneys, but the observation should be kept in mind in connection with long-term feeding of high sucrose or lactose diets.

[5] The STARCH diets contained either more water or had a lower energy density that led to a higher food and food water intake and they are therefore not suitable for comparison of water metabolism with the other diets.

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