The Prediction of Urine pH Using Dietary Cations and Anions in Cats Fed Dry and Wet Foods

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ABSTRACT

The objective of these studies was to determine if urine pH can be predicted using the nutrient components of feline foods. One hundred fifty foods (90 dry foods and 60 wet foods) were fed to groups of 10 adult cats (mean, 8.5 years of age) to determine the urine pH of cats fed each food. The food was fed for a period of 7 days, and pH was determined on freshly voided urine on Days 5 to 7 of the test. Through stepwise regression it was determined which cations, anions, and sulfur-containing amino acids were of importance for urine pH prediction. Three models were developed for urine pH prediction. These models included: 1) wet and dry foods; 2) wet only foods; and 3) dry only foods. The cations included in all models were sodium, potassium, and magnesium. Calcium was excluded from the wet only model. The anions for all models were chloride, sulfur, and phosphorus. Including sulfur in the model allowed for the exclusion of methionine and cysteine from the dry model. Urine pH of adult cats can be predicted from the nutrient components of the food, thus reducing the number of animal studies in order to optimize urine pH (for struvite and/or oxalate prevention) for specific products. Separate formulas must be used for dry and wet foods in order to maintain accuracy.

INTRODUCTION

The formation of stones (struvite and calculi) in the urinary tract is a significant clinical problem for companion animals in many countries.[1] Companion animal urine pH is an important determinant in the prevention of stone formation, and a reduction in urine pH has been shown to reduce the incidence of struvite formation. However the acidification of urine may also increase the risk of calcium oxalate formation.[2]

Major dietary contributors to urine pH include sulfur-containing amino acids and a balance of metabolizable cations and anions.[3] The cations studied included calcium, magnesium, sodium, and potassium. The anions studied include phosphorus, chloride, and the sulfur amino acids (methionine and cysteine). These cations and anions have been shown to directly effect urine pH in various species, including cats, swine, cattle, horses, and rats.[3–9]

Kienzle and Schuhknect[10] investigated the influence of dietary base excess on observed urine pH. Their study concluded that there was a high correlation between base excess in the food and the mean urine pH ($r^2 = 0.96$). This study, however, did not investigate the influence of inorganic sulfate and other sulfur-containing amino acids (ie, taurine) and only involved 4 dry and 6 wet commercial foods. If methionine, cysteine, or inorganic sulfate content of the diet varies greatly from that utilized to derive the equation, then the model accuracy for the prediction of urine pH could be reduced because of alterations in sulfate excretion in the urine.

To date, no published studies have investigated the effects of total dietary cations and anions including sulfur in relation to feline urine pH. It is hypothesized that the use of dietary sulfur in addition to the above listed cations and anions can lead to a more accurate prediction of urine pH.

MATERIALS AND METHODS

Animals and Foods

Forty adult cats were utilized in the study (mean = 8.5 years of age). The cats were cared for in accordance with Institutional Animal Care and Use Committee protocols. The cat's primary living space was cleaned twice daily. Throughout the duration of the experiment, cats were given opportunities for exercise and provided human interaction that included, but was not limited to, play (toys), grooming, and other human-cat interactions (ie, petting). Water was available ad libitum throughout the entire experiment. The range of nutrients for all dry (90) and wet (60) foods are presented in Tables 1 and 2. Each food was formulated in accordance with the Association of American Feed Control Officials[11] nutrient guide for cats and balanced to meet growth and adult maintenance. Each food was fed to a group of 10 cats to maintain body weight. Each day, food was offered at 6-hour intervals at 0600, 1200, 1800, and 2400 by an automatic feeding system (Cat Mate® C-50 Automatic Pet Feeder, Surrey, England) to ensure that fresh food was available at all times. Excess food was removed daily and orts were weighed and recorded. Food samples were collected for nutrient content analysis.

Sampling and Analyses

Freshly voided urine samples were collected twice per day on Days 5, 6, and 7 and were measured via a pH meter (Fisher Scientific Accumet® AR 15, Vernon Hills, Illinois). All feed samples were analyzed for moisture (method 930.15), calcium (method 968.08), sodium (method 968.08), potassium (method 968.08), magnesium (method 968.08), chloride (method 969.10), sulfur (method 923.01), phosphorus (method 965.17), and methionine and cysteine (method 994.12) according to the Association of Official Analytical Chemists.[12]

Table 1. Analyzed Nutrients and Observed Urine pH of the 90 Dry Foods Used in Feline Urine pH Studies.

Nutrient, 100% Dry Matter Basis	Minimum	Maximum	Average	Standard Deviation
Sodium	0.198	0.647	0.356	0.084
Potassium	0.307	1.542	0.801	0.200
Chloride	0.412	1.321	0.826	0.183
Sulfur	0.465	1.149	0.726	0.169
Calcium	0.585	1.269	0.906	0.152
Magnesium	0.043	0.182	0.086	0.038
Phosphorus	0.486	1.064	0.761	0.097
Methionine	0.493	3.546	0.933	0.389
Cysteine	0.378	1.070	0.654	0.161
Observed urine pH	5.792	7.115	6.402	0.312

Statistics

Data were analyzed using the General Linear Models procedure of SAS[13] in order to determine the means, standard deviation, minimum, and maximum for observed nutrients across foods. Data was then analyzed to predict urine pH by using the Regression procedure of SAS.[13] Regression analysis was done to determine if calcium, sodium, potassium, magnesium, chloride, sulfur, phosphorus, methionine, and/or cysteine contributed to the prediction of urine pH.

Table 2. Analyzed Nutrients and Observed Urine pH of the 60 Wet Foods Used in Feline Urine pH Studies.

Nutrient, 100% Dry Matter Basis	Minimum	Maximum	Average	Standard Deviation
Sodium	0.267	1.227	0.394	0.163
Potassium	0.643	1.228	0.925	0.120
Chloride	0.172	2.876	0.865	0.395
Sulfur	0.237	2.763	0.840	0.302
Calcium	0.469	1.413	0.971	0.231
Magnesium	0.044	0.351	0.088	0.043
Phosphorus	0.420	1.144	0.821	0.152
Methionine	0.345	2.005	1.326	0.342
Cysteine	0.251	0.866	0.401	0.107
Observed urine pH	5.845	7.337	6.457	0.326

RESULTS

After the conclusion of all 150 urine pH studies, the nutrients and observed urine pH values were used to challenge previously published models.[3,4,10] These data were then plotted and are represented in Figures 1 and 2. These models failed to accurately predict the average urine pH of the foods used in the current study ($r^2 = 0.25$, 0.25, and 0.12, respectively).

A new model was developed using previously known cations and anions that effect urine pH with the addition of sulfur in cats fed dry and wet foods. Individual mean urine pH per cat (1491 individual urine pH means) was then regressed to the nutrient content (100% dry matter basis) of the food consumed.

Stepwise regression was used to determine which cations and anions were of predictive importance. The cations included in the dry and wet model were sodium, calcium, potassium, and magnesium, whereas the anions were chloride, sulfur, phosphorus, and the amino acids methionine and cysteine (Table 3). This analysis resulted in the following prediction equation for both wet and dry foods:

$$\text{Urine pH} = 6.99 + (1.29 \times \text{sodium}) + (0.78 \times \text{potassium}) - (0.81 \times \text{chloride}) - (0.49 \times \text{sulfur}) + (0.12 \times \text{calcium}) + (1.22 \times \text{magnesium}) - (0.60 \times \text{phosphorus}) - (0.22 \times \text{methionine}) - (0.27 \times \text{cysteine})$$

The new model accounted for 37% variation in individual (n = 1491) observed urine pH and 56% of the variation observed in average (n = 150) urine pH in the cats fed 150 foods (Table 3 and Figure 3).

To determine if separating the food types (dry vs wet) resulted in higher accuracy in urine pH prediction, 2 more models (dry only and wet only) were developed. The cations included in the wet model were sodium, potassium, and magnesium, whereas the anions were chloride, sulfur, phosphorus, and the sulfur amino acids methionine and cysteine. Calcium was excluded from the model (Table 4). This analysis resulted in the following prediction equation for wet foods:

$$\text{Urine pH (wet foods)} = 7.03 + (1.43 \times \text{sodium}) + (0.93 \times \text{potassium}) - (1.16 \times \text{chloride}) - (0.30 \times \text{sulfur}) + (4.76 \times \text{magnesium}) - (0.92 \times \text{phosphorus}) - (0.41 \times \text{methionine}) + (0.34 \times \text{cysteine})$$

The new model accounted for 45% variation in individual (n = 596) observed urine pH and 70% of the variation observed in average (n = 60) urine pH in the cats fed 60 wet foods (Table 4 and Figure 4).

The cations included in the dry model were sodium, potassium, magnesium, and calcium, whereas the anions were chloride, sulfur, and phosphorus. Methionine and cysteine were excluded from this model. This analysis resulted in the following prediction equation for dry foods:

$$\text{Urine pH (dry foods)} = 7.03 + (1.00 \times \text{sodium}) + (1.00 \times \text{potassium}) - (0.93 \times \text{chloride}) - (1.61 \times \text{sulfur}) + (0.89 \times \text{calcium}) + (1.58 \times \text{magnesium}) - (1.04 \times \text{phosphorus})$$

Table 3. Urine pH Prediction Models Determined by Stepwise Regression for Individual Cats (n = 1491) Fed 150 Dry and Wet Foods Using the Nutrient Components of the Food (% dry matter basis).

Model	Sodium	Potassium	Chloride	Sulfur	Calcium	Magnesium	Phosphorus	Methionine	Cysteine	Intercept	r^2
1	—	—	-0.34 ± 0.03	—	—	—	—	—	—	6.71 ± 0.03	0.06
2	—	—	-0.53 ± 0.04	—	—	3.28 ± 0.26	—	—	—	6.58 ± 0.03	0.15
3	—	—	-0.58 ± 0.03	-0.48 ± 0.04	—	4.03 ± 0.26	—	—	—	6.94 ± 0.04	0.23
4	—	—	-0.58 ± 0.03	-0.51 ± 0.04	—	4.01 ± 0.25	—	—	-0.39 ± 0.05	7.17 ± 0.05	0.27
5	—	0.34 ± 0.06	-0.55 ± 0.03	-0.58 ± 0.04	—	3.28 ± 0.28	—	—	-0.32 ± 0.05	6.93 ± 0.06	0.28
6	0.98 ± 0.12	0.55 ± 0.06	-0.78 ± 0.04	-0.58 ± 0.04	—	2.03 ± 0.31	—	—	-0.15 ± 0.05	6.61 ± 0.07	0.31
7	1.13 ± 0.12	0.73 ± 0.07	-0.77 ± 0.04	-0.48 ± 0.04	—	1.27 ± 0.32	—	-0.21 ± 0.02	-0.25 ± 0.05	6.66 ± 0.07	0.35
8	1.25 ± 0.12	0.78 ± 0.06	-0.80 ± 0.04	-0.57 ± 0.04	—	1.24 ± 0.15	-0.48 ± 0.07	-0.22 ± 0.02	-0.29 ± 0.05	7.01 ± 0.09	0.37
9	1.29 ± 0.12	0.78 ± 0.06	-0.81 ± 0.04	-0.49 ± 0.04	0.12 ± 0.07	1.22 ± 0.31	-0.60 ± 0.10	-0.22 ± 0.02	-0.27 ± 0.05	6.99 ± 0.09	0.37

Table 4. Urine pH Prediction Models Determined by Stepwise Regression for Individual Cats (n = 596) Fed 60 Wet Foods Using the Nutrient Components of the Food (% dry matter basis).

Model	Sodium	Potassium	Chloride	Sulfur	Calcium	Magnesium	Phosphorus	Methionine	Cysteine	Intercept	r^2
1	—	—	—	-0.32 ± 0.05	—	—	—	—	—	6.73 ± 0.05	0.06
2	—	—	-0.20 ± 0.04	-0.35 ± 0.05	—	—	—	—	—	6.93 ± 0.06	0.09
3	2.00 ± 0.15	—	0.86 ± 0.06	-0.22 ± 0.05	—	—	—	—	—	6.60 ± 0.06	0.29
4	1.95 ± 0.15	—	-0.86 ± 0.06	-0.21 ± 0.05	—	—	—	-0.21 ± 0.04	—	6.89 ± 0.08	0.32
5	2.01 ± 0.15	0.71 ± 0.12	-0.89 ± 0.06	-0.27 ± 0.05	—	—	—	-0.25 ± 0.04	—	6.31 ± 0.13	0.36
6	2.06 ± 0.14	0.84 ± 0.11	-0.94 ± 0.06	-0.24 ± 0.05	—	—	-0.57 ± 0.09	-0.34 ± 0.04	—	6.81 ± 0.15	0.40
7	1.47 ± 0.16	0.86 ± 0.11	-1.13 ± 0.06	-0.27 ± 0.04	—	4.41 ± 0.61	-0.84 ± 0.10	-0.36 ± 0.04	—	7.07 ± 0.15	0.45
8	1.43 ± 0.16	0.93 ± 0.11	-1.17 ± 0.06	-0.30 ± 0.04	—	4.76 ± 0.62	-0.92 ± 0.10	-0.41 ± 0.05	0.34 ± 0.14	7.03 ± 0.15	0.45

Table 5. Urine pH Prediction Models Determined by Stepwise Regression for Individual Cats (n = 895) Fed 90 Dry Foods Using the Nutrient Components of the Food (% dry matter basis).

Model	Sodium	Potassium	Chloride	Sulfur	Calcium	Magnesium	Phosphorus	Methionine	Cysteine	Intercept	r^2
1	—	—	-0.93 ± 0.06	—	—	—	—	—	—	7.17 ± 0.05	0.20
2	—	0.49 ± 0.05	-0.96 ± 0.06	—	—	—	—	—	—	6.80 ± 0.06	0.27
3	—	0.96 ± 0.06	-0.88 ± 0.05	-0.99 ± 0.07	—	—	—	—	—	7.08 ± 0.06	0.40
4	1.21 ± 0.14	1.19 ± 0.06	-1.09 ± 0.06	-1.29 ± 0.08	—	—	—	—	—	6.86 ± 0.06	0.44
5	0.97 ± 0.15	1.16 ± 0.06	-1.08 ± 0.06	-1.40 ± 0.08	0.39 ± 0.07	—	—	—	—	6.68 ± 0.07	0.46
6	1.16 ± 0.15	1.19 ± 0.06	-1.03 ± 0.06	-1.51 ± 0.08	0.88 ± 0.10	—	-1.05 ± 0.15	—	—	6.99 ± 0.08	0.49
7	1.00 ± 0.15	1.00 ± 0.08	-0.93 ± 0.06	-1.61 ± 0.08	0.89 ± 0.10	1.58 ± 0.48	-1.04 ± 0.15	—	—	7.03 ± 0.08	0.49

The new model accounted for 49% variation in individual (n = 895) observed urine pH and 73% of the variation observed in average (n = 90) urine pH in the cats fed 90 dry foods (Table 5 and Figure 5).

DISCUSSION

The formation of stones (struvite and calculi) in the urinary tract is a significant clinical problem for dogs and cats. When urine becomes supersaturated with minerals (increased urinary excretion of composite minerals; magnesium, ammonium and phosphate), and the urine pH is favorable to crystallization (more alkaline; >7.0 pH), minerals precipitate out of solution to form crystals.[1,14] These crystals then accumulate to form uroliths (struvite, oxalate, etc.). The extent, size, and shape of the uroliths is dependent on whether the conditions in the kidney are ideal for the urolith growth or if the urolith can be dissolved and excreted without complications (urethral plug).[14]

The manipulation of urine pH through nutrition to prevent stone formation in cats has been studied extensively.[3,15–18] The formation of struvite uroliths are often associated with foods that are high in magnesium, favor an alkaline urine pH, and are more common in young and adult cats (ages 1 to 7 years).[14] Decreasing urine pH (<6.6) has been shown to have a greater effect on reducing the struvite-forming potential than changing the concentration of the components of struvite.[3]

Although reducing the urine pH for struvite management is the goal for many pet food formulations, this may not be ideal for older cats (ages 7 to 9 years), which have a greater potential to form calcium oxalate stones. The widespread use of magnesium-restricted and urine-acidifying foods (<6.3 pH) to control struvite in cats has been implicated in the increase of calcium oxalate urolith incidences.[14]

Given these complex circumstances, having a means to predict urine pH via the nutrient composition of the food prior to or without having to feed the food to animals would be of significant value to the pet food industry (reduced animal testing, costs associated with reformulations, etc.). It has been previously demonstrated that the cation and anion content in the food was highly correlated with and directly affected the urine pH in cats.[3,4,10]

Kienzle and Schuhknecht[10] studied the effect of struvite reducing foods on urine pH in cats fed 3 wet, 3 dry, and 4 struvite-reducing commercial foods. The dietary cations, anions, and amino acids that were shown to affect urine pH were calcium, magnesium, sodium, potassium, methionine, cysteine, phosphorus, and chloride. The authors found that there was a high correlation between base excess and the mean urine pH. The linear equation derived from the study accounted for 96% of the variation in the foods used in the study. However, when applied to all 150 foods (dry and wet) in the present study, the linear equation only accounted for 25% of the variation seen in urine pH values (Figure 1).

Kienzle and Wilms-Eilers[4] studied the effects of ammonium chloride and carbonates on acid-base balance in cats. They also found that dietary calcium, magnesium, sodium, potassium, methionine, cysteine, phosphorus, and chloride were the cations, anions, and amino acids affecting urine pH. However, when base excess exceeded the -400 to -500 mmol/kg dry matter, the accuracy to predict urine pH was increased via a parabolic equation. The new equation accounted for 99% of the variation in urine pH values of the 13 experimental foods studied. Although this equation has a high degree of accuracy for their study, when applied to all 150 foods used in the present study, the equation only accounted for 25% of the variation seen in urine pH values (Figure 1).

Markwell et al[3] studied the effects of cations and anions on urine pH in cats fed 32 canned foods in order to predict urine pH. The dietary cations, anions, and amino acid that affected urine pH were calcium, sodium, potassium, phosphorus, methionine, and chloride. Their equation accounted for 36% of the variation seen in their observed urine pH values. When applying their equation to the 60 wet foods used in the present study, the equation only accounted for 12% of the variation seen in the pH values (Figure 2).

The failure of these previous models/equations to accurately predict the urine pH using the nutrient content of the foods in the present study could be the result of limited data sets or not taking into account the total sulfur content of the foods. Although methionine and cysteine are considered to be highly available sulfur-containing compounds, other sulfur sources are used in the pet food industry to reduce urine pH in companion animal foods. Sources of sulfur commonly used to lower urine pH in feline foods include sodium bisulfate, calcium sulfate, and potassium sulfate. Other sulfur-containing compounds utilized in these foods and commonly used in commercials foods include sulfites (preservatives), sodium bisulfate, ferrous sulfate, manganese sulfate, chondroitin sulfate, lipoic acid, thiamine, biotin, and taurine.

Magee et al[19] studied the contribution of dietary protein and inorganic sulfur to total urinary sulfate in humans and found that urinary sulfate from protein sources had a strong correlation with urinary nitrogen ($r^2 = 0.86$). Inorganic sulfur (sulfites) was the difference between total sulfate in urine minus the sulfate derived from protein sources. The estimated contribution of inorganic sulfur to total urinary sulfate in humans ranged from 20% to 30%.

As indicated earlier, sodium bisulfate has been shown to lower urine pH in cats.[20] When compared with phosphoric acid, the sodium bisulfate-containing foods were able to maintain similar urine pH and no differences were observed between the 2 dietary acidifiers. Ammonium sulfate has also been shown to be an effective dietary acidifier to reduce urine pH in rats. Emerick and Lu[9] demonstrated that ammonium sulfate was equivalent in reducing urine pH when com-

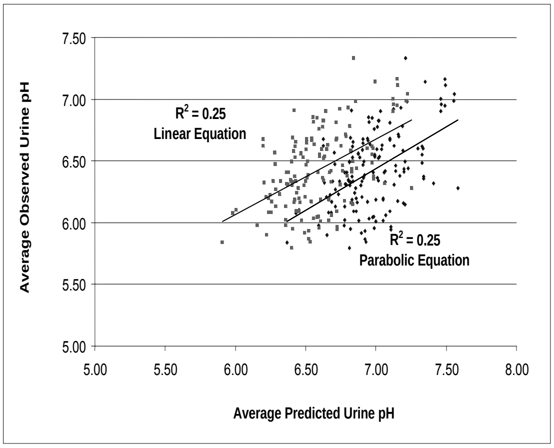

Figure 1. Prediction of feline urine pH using Kienzle and Wilms-Eilers[4] (parabolic) and Kienzle and Schuhknecht[10] (linear) equations for 150 feline foods (90 dry and 60 wet) used in the current study. Linear urine pH = 6.79 + (0.0021 × base excess); parabolic urine pH = 7.1 + (0.0019 × base excess) + ((9.7×10^{-7}) × base excess). Base excess = (49.9 × calcium) + (82.3 × magnesium) + (43.5 × sodium) + (25.6 × potassium) - (64.6 × phosphorus) - (13.4 × methionine) - (16.6 × cysteine) - (28.2 × chloride); nutrients on g/kg dry matter.

pared woth ammonium chloride in rats. As a result, both compounds were effective in reducing the incidence of urolith formation in rats fed a highly available silica source (tetraethylorthosilicate).

In the present study, sulfur was a key nutrient for lowering the urine pH in both wet and dry feline foods. When dietary sulfur (sulfate) and other anions (chloride and phosphorus) are absorbed, there is a shift in the cation-anion balance to a more negative state (toward metabolic acidosis). This results in an increase in arterial concentration of hydrogen ions. The body tries to maintain a slightly alkaline arterial blood pH (approximately 7.4) by responding to this increase in hydrogen ions through 4 processes.[21] The processes include: 1) extracellular buffering; 2) intracellular and bone buffering; 3) respiratory buffering; and 4) renal excretion of the extra hydrogen ions. The first 3 processes take action to minimize the increase in hydrogen concentration until the kidney restores acid-base balance. The kidney restores the acid-base balance by eliminating the excess hydrogen ions in the urine,[21] thus reducing urine pH.

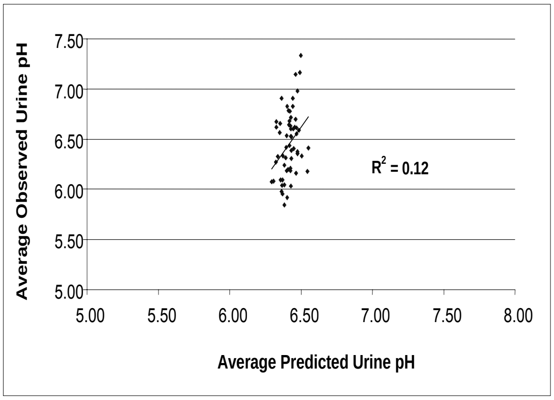

Figure 2. Prediction of feline urine pH using Markwell et al[3] equation used for the 60 feline wet foods used in the study. pH = 6.42 + (0.572 × calcium) + (0.727 × sodium) + (0.674 × potassium) - (0.731 × phosphorus) - (0.546 × methionine) - (0.183 × chloride); nutrients on g/100 g as-fed basis.

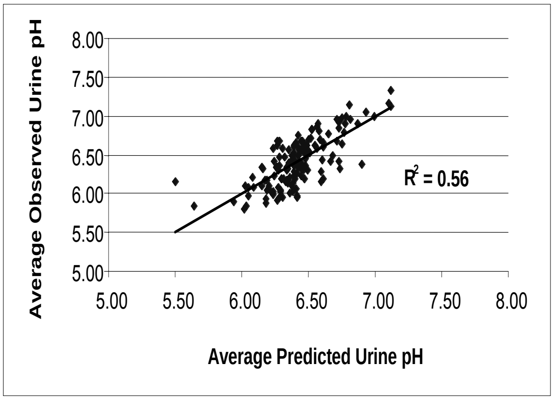

Figure 3. Average predicted urine pH vs average observed urine pH of 150 feline foods (90 dry and 60 wet foods). Each data point for the average observed urine pH represents the mean urine pH of 10 cats fed a particular food. Urine pH = 6.99 + (1.29 × sodium) + (0.78 × potassium) - (0.81 × chloride) - (0.49 × sulfur) + (0.12 × calcium) + (1.22 × magnesium) - (0.60 × phosphorus) - (0.22 × methionine) - (0.27 × cysteine).

In the current study, taking into account the total calcium, magnesium, potassium, sodium, phosphorus chloride, sulfur methionine, and cysteine content of the food accounted for 73% and 70% of the variation in the observed average urine pH in dry only and wet only models, respectively. It appears that different nutrients affects urine pH when separating the models into dry only and wet only foods. The signs of the coefficients for the dry food only are in agreement with what was expected.

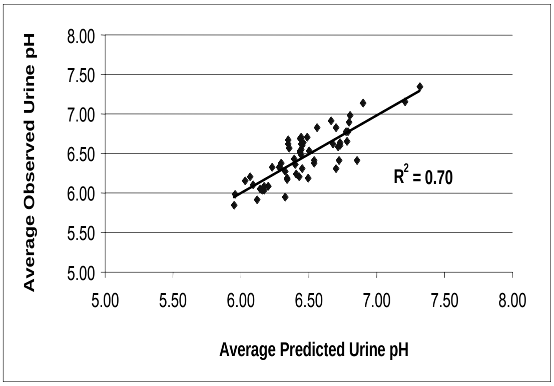

Figure 4. Average predicted urine pH vs average observed urine pH of 60 feline wet foods. Each data point for the average observed urine pH represents the mean urine pH of 10 cats fed a particular food. Urine pH (wet foods) = 7.03 + (1.43 × sodium) + (0.93 × potassium) - (1.16 × chloride) - (0.30 × sulfur) + (4.76 × magnesium) - (0.92 × phosphorus) - (0.41 × methionine) + (0.34 × cysteine).

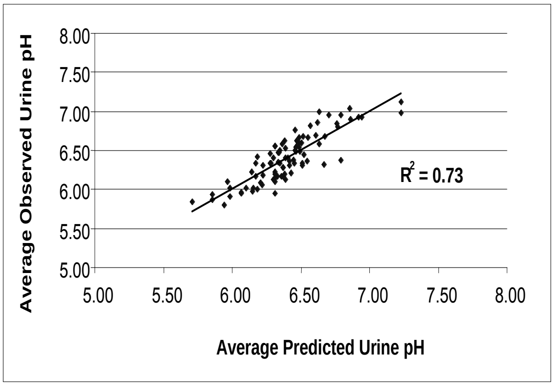

Figure 5. Average predicted urine pH vs average observed urine pH of 90 feline dry foods. Each data point for the average observed urine pH represents the mean urine pH of 10 cats fed a particular food. Urine pH (dry foods) = 7.03 + (1.00 × sodium) + (1.00 × potassium) - (0.93 × chloride) - (1.61 × sulfur) + (0.89 × calcium) + (1.58 × magnesium) - (1.04 × phosphorus).

Increases in pH were directly related to increases in calcium, potassium, sodium, and magnesium and inversely related to sulfur, phosphorous, and chloride. The wet food model also included methionine and cysteine. The coefficient of methionine is in agreement with past studies[3]; however, cysteine in the wet model was shown to be directly related to an increase in urine pH. It is uncertain why this occurred. It is well known that when cysteine is metabolized in the body there is a release in sulfate. As a result, cysteine should have an inverse relationship with urine pH.

In conclusion, urine pH of adult cats can be predicted from the nutrient components of the food, thus reducing the number of animal studies in order to optimize urine pH (for struvite and/or oxalate prevention) for specific products. Separate formulas must be used for dry and wet foods in order to maintain accuracy. In addition, number of foods, the range of the nutrients, and observed urine pH are broad enough to cover most commercial feline dry and wet foods in the marketplace. With this knowledge, pet food companies can formulate foods or veterinarians can provide supplements or recommendations for an optimal urine pH by managing cation-anion balance.

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REFERENCES

1. Robertson WG, Jones JS, Heaton MA, Stevenson AE, Markwell PJ: Predicting the crystallization of urine from cats and dogs with respect to calcium oxalate and magnesium ammonium phosphate (struvite). *J Nutr* 2002;132:1637S-1641S.
2. Jackson JR, Kealy RD, Lawler DF, Ballam J, Laflamme DP: Long-term safety of urine acidifying diets for cats. *Vet Clin Nutr* 1995;2:100-107.
3. Markwell PJ, Buffington CT, Smith BHE: The effect of diet on lower urinary tract diseases in cats. *J Nutr* 1998;128:2753S-2575S.
4. Kienzle E, Wilms-Eilers S: Struvite diet in cats: Effect of ammonium chloride and carbonates on acid base balance of cats. *J Nutr* 1994;124:2652S-2659S.
5. DeRouchey JM, Hancock JD, Hines RH, et al: Effects of dietary electrolyte balance on the chemistry of blood and urine in lactating sows and sow litter performance. *J Anim Sci* 2003;81:3067-3074.
6. Patience JF, Chaplin RK: The relationship among undetermined anion, acid-base balance, and nutrient metabolism in swine. *J Anim Sci* 1997;75:2245-2452.
7. Goff JP, Horst RL: Use of hydrochloric acid as a source of anions for prevention of milk fever. *J Dairy Sci* 1998;81:2874-2880.
8. Schreier CJ, Emerick RJ: Diet calcium carbonate, phosphorus and acidifying and alkalizing salts as factors influencing silica urolithiasis in rats fed tetraethylorthosilicate. *J Nutr* 1986;16:823-830.
9. Emerick RJ, Lu D. A possible synergism of dietary phosphate and urine acidifying salts in preventing silica urolithiasis in a rat model. *J Nutr* 1987;117:1603-1608.

10. Kienzle E, Schuhknecht A: Struvite stone dietetics: 1. Effect of different feed rations on the urine pH value of cats. *Dtsch Tierarztl Wochenschr* 1993;100:198-203.
11. Association of American Feed Control Officials: *2004 Official Publication of the Association of American Feed Control Officials Incorporated*. Oxford, IN.
12. Association of Official Analytical Chemists (AOAC). *1995 Official Methods of Analysis.* AOAC: Washington, DC.
13. SAS: *1989 SAS/STAT® User's Guide (Release 6.03)*. SAS Institute. Inc.: Cary, NC.
14. Houston DM, Moore AEP, Favrin MG, Hoff B: Feline urethral plugs and bladder uroliths: a review of 5484 submissions 1998-2003. *Can Vet J* 2003;44:974-977.
15. Buffington CA, Rogers QA, Morris JG, Cook NE: Feline struvite urolithiasis:magnesium effect depends upon urinary pH. *Fel Pract* 1985;15:29-33.
16. Buffington CA: Feline struvite urolithiasis: effect of diet. *Proceedings of the 3rd Annual Symposium of the European Society of Veterinary Nephrology and Urology*. Intercongress: Barcelona Spain; 1988:73-112.
17. Marshall W, Robertson WG: Nomograms for the estimation of the saturation of urine with calcium oxalate, calcium phosphate, magnesium ammonium phosphate, uric acid, sodium acid urate, ammonium acid urate and cystine. *Clin Chim Acta* 1976;72:253-260.
18. Taton GF, Hamar DW, Lewis LD: Urinary acidification in the prevention and treatment of feline struvite urolithiasis. *J Am Vet Med Assoc* 1984;184:437-443.
19. Magee EA, Curno R, Edmond LE, Cummings JH: Contribution of dietary protein and inorganic sulfur to urinary sulfate: toward a biomarker or inorganic sulfur intake. *Am J Clin Nutr* 2004;80:137-142.
20. Spears JK, Grieshop CM, Fahey GC, Jr.: Evaluation of sodium bisulfate and phosphoric acid as urine acidifiers for cats. *Arch Anim Nutr* 2003;57:389-398.
21. Rose BD, Post TW: *Clinical Physiology of Acid-Base and Electrolyte Disorders*. McGraw-Hill Medical Publishing Division: New York, New York; 2000.