Ca^{2+}, K^+, and Na^+ content of corn bran during passage through pig gastrointestinal tract: Comparison with model predictions

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Dietary fibers may limit mineral bioavailability through ion-exchange processes. To critically test this hypothesis, it is necessary to know the extent of mineral binding under gastrointestinal conditions. This work describes the merits and limits of methods devised to determine the extent of ion binding by dietary fiber in vivo. Corn bran was employed as the dietary fiber source. Bran was fed to pigs, then retrieved along with digesta from various gastrointestinal locations. Corn bran cation content (Na^+, K^+, and Ca^{2+}) was determined by energy-dispersive X-ray spectroscopy (EDX). EDX-determined ion contents were partitioned into bound and free fractions based on a previously developed ion-exchange model, the estimated free (aqueous) concentrations of electrolytes in the digesta, and the aqueous solution content of hydrated corn bran. The model provided estimates of bound Na^+, K^+, Mg^{2+}, and Ca^{2+} for upper gastrointestinal locations. Colon ion concentrations were too high to be used in the model. Sodium values determined by EDX were insufficiently precise to test the adequacy of the model. Values for K^+ and Ca^{2+} content determined by EDX analysis agreed well with model predictions when the extent of corn bran hydration was known explicitly. Correlation between model and observed values was poorer when bran hydration extent was simply estimated. Model predictions based on measured ion concentrations in the digesta suggest that calcium associated with corn bran in jejunum and ileum segments was predominantly bound, while most K^+ and Na^+ was free. It was concluded that corn bran can bind sufficient Ca^{2+} in the upper gastrointestinal tract to impact Ca^{2+} absorption to a small extent under certain dietary regimes.

Keywords: dietary fiber; bioavailability; swine; ion exchange

Introduction

The impact of dietary fiber on human mineral absorption is an unsettled question. Some human and animal-model studies suggest an impairment of mineral absorption by dietary fiber, apart from the similar influence of phytic acid.[1-4] Other studies contradict this view.[5-9] Much of the discrepancy among these observations arises from the large variation in individual responses, period of data collection, and the general difficulties associated with conducting long-term mineral balance studies.[10,11]

An alternative approach for addressing the dietary fiber-mineral bioavailability issue is to delineate the potential chemical or physiological mechanism(s) by which dietary fiber may influence mineral absorption. Two mechanisms have been proposed: (1) fiber diminishes nutrient uptake by altering mucosal structure and physicochemical processes;[12-14] (2) fiber binds minerals, reducing their concentration (activity) at sites of absorption in the gastrointestinal (GI) tract.[15,16] The substantial mineral-binding capability of various dietary fibers is readily demonstrated in vitro.[17-19] However, in vitro observations generally fail to consider fully how competing electrolytic ions influence the binding of minerals such as iron, zinc, or calcium, thus providing only a rough approximation to GI ionic conditions.[20-25] Conclusions drawn from in vitro experi-

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ments under simplified conditions may have limited validity when applied to the in vivo situation. A proper test of the hypothesis that fiber exerts its (putative) influence on mineral absorption via ion-binding mechanisms should include an examination of the mineral content of dietary fiber under authentic GI conditions.

For the present study, K^+, Na^+, and Ca^{2+} contents of corn bran fragments recovered from several pig GI locations were measured by energy-dispersive X-ray spectroscopy (EDX). Corn bran (90% total dietary fiber)[26] was selected as a model dietary fiber because it remains intact during passage through the GI tract[27] and is a common feed component. Mineral analysis by EDX of interior sections of retrieved bran fragments provides a measure of ion content unbiased by mineral concentrations in surface-adhering digesta. It is not necessary to wash the bran free of digesta contamination, risking loss of ions from the bran. However, EDX analysis does not distinguish between ions bound to corn bran from unbound minerals in the aqueous phase of the digesta that are adventitiously "trapped" within the matrix of the hydrated bran particle. The distinction is important because binding reduces ion activity, and thus absorption rate, while adventitious association does not affect ion activity. A model describing the ion-exchange properties of corn bran under highly variable ionic conditions[28] was utilized to differentiate the two. The objective of this study is to demonstrate the value and limitations of the model and the methods employed (EDX analysis, procedures for estimating free ion concentrations, etc.) in delineating the potential for dietary fibers to limit mineral availability by ion binding.

Materials and methods

Ions present in a corn bran particle as it travels through the GI tract are distributed between two phases. Ions in the bran solid phase are considered bound, whether through ion exchange or other adsorption processes. Ions in the bran aqueous phase are unbound (free), that is, their activity is uninfluenced by the presence of the bran particle. (Initially, the possibility that there are aqueous-phase–bound ions, i.e., ions bound to soluble ligands within the corn bran tissue spaces, will be ignored.) The unbound-ion content depends on the ion concentration in the digesta and the amount of aqueous phase associated with the bran particle (i.e., its water content or hydration value). The bound ion content will depend on many interrelated factors, including the aqueous-phase ion activities, solid phase ion-exchange capacity, and ion-exchange equilibrium constants. Bound-ion content is calculated from the set of simultaneous equations that describe the ion-exchange equilibria (Equation 1) and maintenance of solid-phase electrical neutrality (Equation 2).[28]

$$K^i_H = \frac{(H^+)^{Z_i} M_i}{[X_i] (\gamma_i M_H e^{\Lambda_H M_H})^{Z_i}} \quad (1)$$

$$\Sigma^{Z_i M_i} = 1 \quad (2)$$

K^i_H is the equilibrium constant for the exchange of H^+ for cation i, and (H^+) is the aqueous phase proton activity. $[X_i]$, Z_i, and γ_i are the aqueous phase concentration, charge, and activity coefficient, respectively, of cation i. M_i is the solid phase ion mole fraction. Λ_H is an empirical constant. Corn bran used in this study had a cation exchange capacity of 212 microequivalents per g dry weight (μeq/g DW).[28] Exchange constants for the major cations of interest in this work are: Na^+, 1×10^{-5}; K^+, 1.5×10^{-5}; Ca^{2+}, 4×10^{-10}; and Mg^{2+}, 2×10^{-10}. The value for the model parameter Λ_H is 7.6.

Modeling and in vitro testing were conducted at 25° C instead of physiological temperature because the digesta, and therefore the corn bran, was subjected to a wide range of temperatures during retrieval and processing. Thus the temperature at which the ion binding occurred was uncontrolled and indeterminant. The effect of temperature on ion-binding selectivity of corn bran is unknown, but is expected to be small.[29]

Details concerning care and feeding of pigs, retrieval of digesta and corn bran from various GI locations, and EDX mineral analysis of bulk sections are given elsewhere.[30,31] The following is a summary of those procedures.

Twelve pigs were fed diets consisting of 10% (dry weight basis) corn bran, 20% soybean meal, 67% corn grits, and vitamins, with or without mineral supplementation. Mineral-supplemented diets contained 8.8 g/Kg calcium and 4.9 g/Kg phosphorus, while unsupplemented diets contained 1.6 g/Kg calcium and 2.3 g/Kg phosphorus. At time of slaughter, digesta was sampled from the stomach, proximal jejunum, distal jejunum, ileum, proximal, and distal colons. Digesta wet weights were recorded. Samples were freeze-dried and stored at room temperature. Differences between digesta wet and dry weights served as a measure of the water content of the digesta at each GI location. For each pig, at each GI location, four corn bran fragments were recovered from dry digesta samples and prepared as bulk specimens for EDX mineral analysis by direct embedding in acrylic resin and transverse sectioning with a microtome. Not all digesta samples had sufficient material for analysis. Na^+, K^+, and Ca^{2+} concentrations were determined in three separate interior areas of a bran section, giving a total of twelve observations for each pig/GI location combination.

To estimate in vivo ionic conditions, the fraction of ions in the digesta unbound by high molecular weight or insoluble material was determined. Digesta (1–2 g) was rehydrated at 38° C with 30 mL deionized water for 2 hr. The slurry pH was recorded (at 25° C), then the sample was centrifuged (2.5 hr at 146,000g). The supernatant was ultrafiltered (1,000 nominal molecular weight cut-off), then wet ashed for mineral analysis by atomic absorption spectroscopy. Ammonia concentration in the ultrafiltrate was determined by ion chromatography (IC). The unbound (i.e., free) ion concentration at a particular GI location was calculated based on the measured concentration in the ultrafiltrate and the original water content of the digesta.

For experiments in which GI ionic conditions were simulated in vitro, solutions (100 mL) were prepared containing chloride salts of Na^+, K^+, Mg^{2+}, and Ca^{2+} at concentrations equivalent to those estimated for the selected pig GI locations. Solution pH was controlled with 2.0 mmol/L concentrations of buffers (acetate or 4-morpholineethanesulfonic acid). Corn bran (100 mg) from the same lot as that fed to the pigs, depleted of endogenous minerals by treatment with 50 mmol/L HCl, was added to the simulated-digesta solutions, equilibrated for 2 hr (25° C), recovered by filtration, and analyzed for total and bound ion content by IC.

The ion chromatography module (model 2010i, Dionex Corp. was equipped with a cation-separating column (HPIC CS-1, Dionex Corp. Sunnyvale, CA), a post-column back-

ground-conductivity suppressor cell, and a conductivity cell. Monovalent and divalent cations were determined in separate runs, employing isocratic elution conditions (5.0 mmol/L HCl for monovalents, 6.0 mmol/L HCl, 2.0 mmol/L meta-(1,3)-phenylenediamine for divalents). Quantitation of eluted ions was performed by a Spectra-Physics 4270 integrator (Spectra-Physics, San Jose, CA).

Results

Table 1 gives the estimated free cation concentrations and pH values of selected GI locations of various pigs. Ammonia concentrations were much lower than other monovalent cation concentrations (data not shown) and thus were not considered further. The pH values of rehydrated digesta samples were within ±0.5 pH units of the values measured on the fresh samples, indicating that the freeze-drying process did not substantially alter sample pH. pH values given in *Table 1* are for the rehydrated digesta. Most digesta samples were rehydrated with more water (10-fold greater, maximum) than their original content to facilitate filtration. Dilution of the digesta may have slightly altered the distribution of free and bound ions. No attempt was made to correct for this dilution effect. Note, however, that free ion concentrations were calculated using original water content values. Although some significant differences in free ion concentrations were apparent between unsupplemented and mineral supplemented diets (data not shown), these differences were considered unimportant for the following analysis. Thus the data from the two diets are not distinguished here.

The selected pig/GI locations listed in *Table 1* represent the subset of locations examined in which estimated free cation concentrations fell within the upper limits (approximately) for which the ion-binding model parameters were established, 150 mmol/L for total monovalents and 10 mmol/L for each divalent cation.[28] Thus the data are limited to upper GI segments, with one exception (pig 503, distal colon). The few locations at which estimated total monovalent cation concentrations were much lower than 50 mmol/L were excluded as well.

To establish the efficacy of the model in estimating the concentration of bound ions in corn bran, a comparison was made between model predictions and experimentally observed (in vitro) values for solutions comprised of free electrolytes at the concentrations estimated for upper GI locations of pigs 510, 513, and 518 *(Figure 1)*. There was generally good agreement between model-predicted and observed values. An analysis of residuals *(Figure 2)* showed that agreement was best for divalent-cation predictions, with a tendency to overestimate the amount bound (up to 6 μmol/g DW). The largest disparities between model and observed values were for Na^+. Bound Na^+ was underestimated by as much as 15 μmol/g DW and overestimated by as much as 32 μmol/g DW (15% of the total exchange capacity of corn bran). Model overestimates of bound Na^+ increased with increasing so-

Table 1 Estimated free cation concentrations at pig GI locations

Pig ID	GI location	pH	Ion concentration (mmol/L)			
			Na^+	K^+	Ca^{2+}	Mg^{2+}
503	Stomach	6.6	87	19	2.0	1.3
	Ileum	8.0	113	28	1.6	4.5
	Distal colon	7.3	66	85	11.8	13.5
510	Stomach	4.9	24	28	3.7	4.3
	Prox jejunum	5.9	67	15	0.9	2.1
	Dist jejunum	5.5	99	22	4.8	14.7
	Ileum	5.3	74	18	4.5	9.4
512	Ileum	7.2	130	29	0.5	1.8
513	Stomach	4.9	32	40	4.6	5.3
	Dist jejunum	6.8	113	29	0.8	3.2
	Ileum	6.9	129	16	0.8	3.1
518	Stomach	4.5	54	35	9.2	3.2
	Prox jejunum	6.1	109	37	5.8	5.5
	Dist jejunum	6.8	137	27	4.3	6.6
522	Stomach	4.6	85	19	1.8	1.1
	Ileum	7.9	123	26	0.7	1.9
524	Stomach	4.3	67	37	4.2	4.4
	Prox jejunum	6.5	103	28	1.9	2.9
	Dist jejunum	5.6	118	21	1.6	3.6
525	Stomach	4.1	22	27	13.6	4.2
	Prox jejunum	5.7	119	29	11.0	7.0
	Ileum	7.7	101	28	8.9	13.7
528	Stomach	4.3	31	30	5.5	4.6
	Dist jejunum	6.8	133	21	0.8	6.6
	Ileum	7.3	122	30	0.5	4.5
530	Stomach	3.2	40	19	15.5	2.5
	Ileum	8.7	119	16	0.6	0.1
533	Dist jejunum	6.4	132	28	1.2	4.0

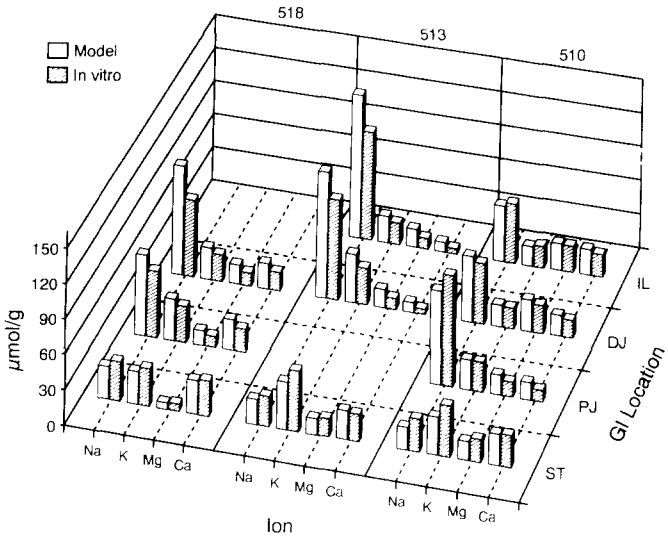

Figure 1 Cation binding to corn bran. Comparison of in vitro-observed and model-predicted binding of Na^+, K^+, Mg^{2+}, and Ca^{2+} to corn bran under ionic conditions approximating various pig GI locations (ST, stomach; PJ, proximal jejunum; DJ, distal jejunum; IL, ileum).

lution Na concentrations *(Figure 2, panel C)*. The residuals of the bound K^+ values were evenly distributed *(Figure 2, panel D)*.

Total ion content of corn bran consists of bound- and unbound-ion fractions. The bound-ion fraction is calculated from equations 1 and 2. The unbound ion content is equal to the aqueous phase concentration of the ion (μmol/mL) multiplied by the hydration value of the tissue (mL/g DW). Corn bran hydration values were 1.4–2.4 mL/g DW for samples equilibrated with simulated-GI salt solutions and recovered by filtration. There was no apparent correlation between solution ionic strength or composition and hydration values (data not shown). *Table 2* gives the model-predicted total ion content of corn bran under the ionic conditions estimated for pig 510 stomach over the 1.4–2.4 mL/g DW hydration range (see *Table 1* for aqueous phase ion concentrations). The ion contents of corn bran retrieved by filtration from the in vitro-simulated solution for this pig/location were well within the model-predicted range *(Table 2)*. Note that the bound fractions of Na^+ and K^+ represent small percentages (<40%) of the total content of each ion, while Ca^{2+}

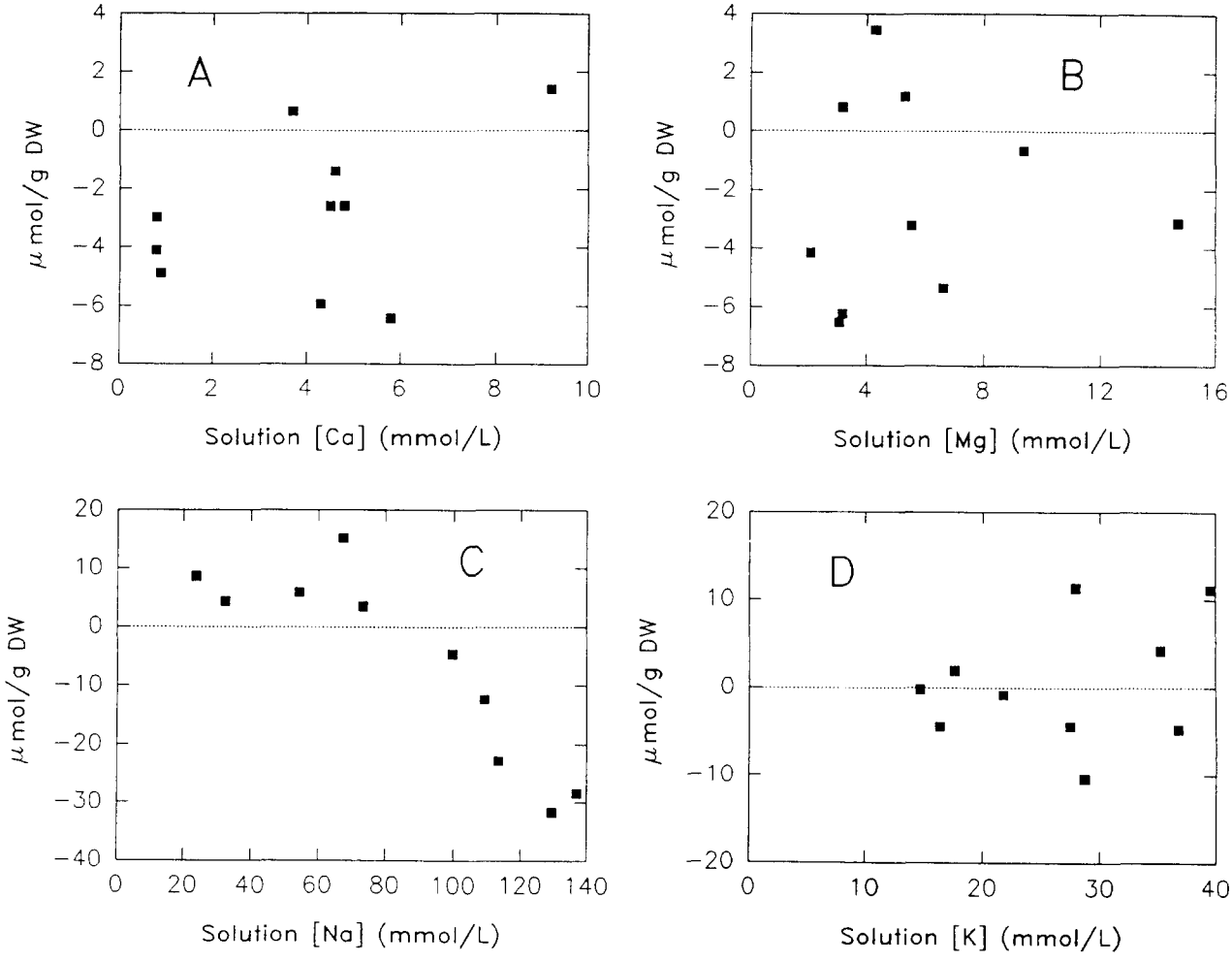

Figure 2 Residuals analysis. Difference between in vitro-observed and model values (observed minus model prediction) for data shown in *Figure 1* as a function of solution ion concentration. Panel A, Ca^{2+}; panel B, Mg^{2+}; panel C, Na^+; panel D, K^+.

Table 2 Total cation content of corn bran under simulated (in vitro) or authentic (in vivo) ionic conditions of pig 510 stomach

Experimental conditions	Ion content (μmol/g)			
	Na^+	K^+	Ca^{2+}	Mg^{2+}
Model-predicted	51–75[a] (19)[b]	71–100 (32)	32–36 (27)	22–26 (16)
In vitro simulated-solution[c]	65 ± 1[d]	87 ± 1	33 ± 1	26 ± 1
In vitro treatment with rehydrated digesta[e]				
Filtered	170 ± 20	100 ± 10	36 ± 5	nd[f]
Freeze-dried	210 ± 30	190 ± 40	39 ± 5	nd
In vivo sample[e]	280 ± 50	240 ± 40	34 ± 8	nd

[a]Range, using 1.4–2.4 mL/g hydration values.
[b]Model estimate of bound ion content.
[c]Ion contents determined by IC.
[d]Mean ± one standard deviation (n = 3).
[e]Ion contents determined by EDX (n = 12).
[f]Not determined.

and Mg^{2+} are predominately in the bound fraction. This pattern of ion distribution between aqueous (unbound) and solid (bound) is typical for the range of GI ionic conditions treated here.

To further test the model predictions of total ion content, a small sample of corn bran (100 mg) enclosed in a nylon-mesh bag was equilibrated with a slurry of pig 510 stomach digesta (10 g DW) that was rehydrated to the same extent as when initially collected. The corn bran was equilibrated for 3 hr at 38° C. Under these conditions, the presence of the added corn bran is not expected to significantly alter the aqueous phase ion concentrations. After treatment, the corn bran was retrieved from the bag, collected on filter paper, and vacuum dried at room temperature (to approximate the standard in vitro sample recovery procedure) or freeze-dried in contact with the digesta slurry (mimicking the in vivo sample processing protocol). Na^+, K^+, and Ca^{2+} contents of filter-collected bran and freeze-dried bran were determined by EDX, to avoid detecting ions associated with any adhering solid digesta *(Table 2)*. The Ca^{2+} contents of either the "filtered" or "freeze-dried" samples compared well with the model-predicted values for total Ca^{2+} content. The K^+ content of the "filtered" bran agreed with the model value, but the "freeze-dried" sample had approximately two-fold higher K^+ content than expected. That the "freeze-dried" K^+ content was higher than the "filtered" sample suggests that hydration of the tissue is greater when processed in the presence of equilibrating solution. The Na^+ content was two–three-fold higher than predicted. The "filtered" versus "freeze-dried" Na^+ content can be, again, attributed to different hydration values, which affect only free ion content. The difference between model-predicted and "filtered" Na^+ values may have resulted from higher-than-estimated Na^+ activity in the rehydrated digesta solution (resulting in greater Na^+ binding), or a high concentration of soluble, but bound, Na^+ invading the corn bran matrix interior. Magnesium was too poorly detected by the EDX instrumentation for quantitative analysis, thus comparison between model and in vitro values for Mg^{2+} was not possible. The close agreement of the Na^+, K^+, and Ca^{2+} contents of the "freeze-dried" corn bran sample with those of the in vivo bran sample (i.e., corn bran retrieved from pig 510 stomach digesta) implies that rehydrated digesta conditions were very similar to the in vivo state *(Table 2)*.

The hydration value of corn bran that was freeze-dried in contact with excess solution was determined by treating bran with a 30 mmol/L KCl solution containing 10 mmol/L Ca^{2+} (pH 6). No K^+ binding is expected to occur under these conditions because of the much higher affinity of corn bran for Ca^{2+}. Therefore the K^+ content reflects only the effective hydration of bran (i.e., 30 μmol K^+ for each mL of solution associated with 1 g of dry corn bran) while in direct contact with solution. The K^+ content determined by EDX was 190 ± 58 μmol/g DW. Thus the hydration value was 6.3 ± 1.9 mL/g DW. This value is several-fold higher than hydration values observed for bran samples collected by filtration. It is consistent with the observation of higher K^+ in the "freeze-dried" than "filtered" samples described in *Table 2*. Ca^{2+} content values were not similarly influenced by hydration value differences because most of the Ca^{2+} present in the bran was bound *(Table 2)*.

Two factors, the large hydration values of freeze-dried bran samples and the substantial uncertainty in EDX-determined ion content values, resulted in an uncritical measure of the efficacy of the model. The model was subjected to a more definitive test by treating corn bran enclosed in a nylon-mesh bag (conditions as described above) with digesta from pig 510 proximal jejunum and pig 513 distal jejunum. The free ion concentrations and slurry pH were determined after equilibrium. The corn bran hydration values of the retrieved samples were measured (2.07 and 1.56 mL/g DW, respectively, for 510 distal jejunum and 513 proximal jejunum samples). Bran ion contents were determined by ion chromatography (IC) and EDX, and compared with the model-predicted values *(Table 3)*. The free ion concentrations and solution pH values

Table 3 Comparison of model-predicted with IC- and EDX-determined total ion content of corn bran equilibrated with pig digesta

Ion	Pig ID	GI location	Ion content (μmol/g)		
			Model-predicted	IC-determined	EDX-determined
Na^+	510	Prox jejunum[a]	222	210 ± 5	402 ± 74[b]
	513	Dist jejunum[c]	216	210 ± 5	348 ± 53
K^+	510	Prox jejunum	63	64 ± 1	79 ± 17
	513	Dist jejunum	62	62 ± 1	74 ± 17
Ca^{2+}	510	Prox jejunum	20	24 ± 1	26 ± 7
	513	Dist jejunum	14	20 ± 1	14 ± 2
Mg^{2+}	510	Prox jejunum	33	34 ± 1	nd[d]
	513	Dist jejunum	28	23 ± 1	nd

[a]Determined solution-free ion concentrations: Na^+, 80 mmol/L; K^+, 20 mmol/L; Ca^{2+}, 2.6 mmol/L; Mg^{2+}, 6.8 mmol/L; pH 5.1.
[b]Mean ± one standard deviation (IC, n = 3; EDX, n = 12).
[c]Determined solution-free ion concentrations: Na^+, 84 mmol/L; K^+, 20 mmol/L; Ca^{2+}, 1.1 mmol/L; Mg^{2+}, 3.8 mmol/L; pH 6.2.
[d]Not determined.

were slightly different from the estimates given in *Table 1*, due perhaps to digesta heterogeneity. With explicit knowledge of the bran sample hydration values and solution free ion concentrations, the model-predicted and IC-determined ion content values agreed to a high degree. EDX-determined Na^+ concentrations were much higher than modeled or IC values, indicating there was systematic bias in EDX Na^+ measurements. EDX K^+ and Ca^{2+} values agreed reasonably well with model and IC values.

Model-predicted K^+ and Ca^{2+} content values are compared to the EDX-measured values of corn bran retrieved from various GI locations (i.e., in vivo samples) in *Table 4*. Although estimates of Na^+ and Mg^{2+} content are generated by the model, the EDX measurements of Na^+ and Mg^{2+} were too imprecise or insensitive for useful comparison. The model values are derived based on the free ion concentrations of the GI location given in *Table 1* and a corn bran hydration value of 6 mL/g DW (because the in vivo bran samples were freeze-dried in the presence of the whole digesta slurry). Model predictions fell within two standard deviations for 22 of 28 (79%) K^+ and 19 of 28 (68%) Ca^{2+} EDX means. Model values outside the two standard deviation range were evenly distributed between over and under estimates. The largest discrepancy between model and observed values occurred with the pig 503 distal colon sample, for which the model greatly overestimates both K^+ and Ca^{2+} content.

Discussion

Using EDX to determine ion concentrations in corn bran has both significant limitations and substantial advantages. Conventional EDX analysis of biological tissues is generally limited to the most abundant ions, Na^+, K^+, Ca^{2+}, and Mg^{2+}. Quantitative determination of Mg^{2+} was not possible, and Na^+ quantitation was marginal for the corn bran samples examined. However, EDX analysis provided direct analysis of K^+ and Ca^{2+} content, free of the potential alterations implicit in other procedures that might have been applied.

The model provides an estimation of bound ion content over the widely varying conditions of the upper GI tract *(Figure 1)*. That these ionic conditions do indeed vary widely is indicated by the data in *Table 1*. Thus it is better to apply the model to explicitly measured conditions than to presume pH and electrolyte concentrations based on generalized estimates for GI locations. For instance, observed pig stomach pH values were substantially higher than the ≤pH 2 widely employed for in vitro simulation.[23,25,32] Stomach pH is raised by food and fiber.[33,34] The pig stomach pH values observed *(Table 1)* were higher than those reported for human subjects following food consumption,[33,35] but comparable to the range of values for pigs measured by Alexander.[36] The concentrations of Na^+ and K^+ observed were consistent with the pattern of mineral fluxes measured in pigs.[36,37]

The model requires knowledge of free ion concentrations, which are difficult to distinguish from bound, soluble ion concentrations when the digesta contains many soluble ion-binding ligands. In the present work it was assumed ions that pass through a 1,000 molecular weight cut-off filter are free. It was also assumed that corn bran from a given GI location was exposed to a homogeneous solution with respect to free ion concentration. Violation of this presumption may account for some of the larger disparities between model and EDX values *(Table 4)*. For comparison of the model with the EDX measurement of total ion content, knowledge of the effective solution phase content (hydration value) of freeze-dried corn bran was important. Hydration values based on in vitro filter collection procedures were much too small *(Tables 2 and 3)*. Although it was anticipated that ions bound to other digesta components may invade the interior spaces of the corn bran, this apparently does not happen. Total Ca^{2+} concentrations in the digesta were many-fold higher than free Ca^{2+} concentrations (data not shown), yet model predictions based on free Ca^{2+} values proved adequate in most cases *(Table 4)*. The model should be applicable

Table 4 Comparison of model-predicted and in vivo-observed K^+ and Ca^{2+} content of corn bran

Pig ID	GI location	Ion content (μmol/g)			
		Model		In vivo (EDX)	
		K^+	Ca^{2+}	K^+	Ca^{2+}
503	Stomach	143	38	278 ± 124	40 ± 8
	Ileum	208	24[a]	201 ± 37	41 ± 4
	Distal colon	575[b]	105[b]	249 ± 38	63 ± 7
510	Stomach	200	49	238 ± 42	34 ± 8
	Prox jejunum	113	20	129 ± 36	31 ± 11
	Dist jejunum	149	47	155 ± 28	49 ± 6
	Ileum	123[a]	51	164 ± 15	43 ± 8
512	Ileum	217	8	163 ± 72	24 ± 8
513	Stomach	277	52[b]	237 ± 29	38 ± 3
	Dist jejunum	214[b]	13	142 ± 16	18 ± 4
	Ileum	121[a]	13[a]	178 ± 25	38 ± 5
518	Stomach	239	84	170 ± 40	69 ± 23
	Prox jejunum	256	61	161 ± 60	49 ± 15
	Dist jejunum	192	48	132 ± 36	52 ± 24
522	Stomach	133	23	114 ± 34	27 ± 5
	Ileum	195	13	179 ± 22	37 ± 22
524	Stomach	255[b]	40	147 ± 23	35 ± 10
	Prox jejunum	205	29	277 ± 101	35 ± 10
	Dist jejunum	150	21	194 ± 39	28 ± 5
525	Stomach	179	116	198 ± 56	119 ± 42
	Prox jejunum	199[b]	100[b]	140 ± 28	64 ± 13
	Ileum	191	88	127 ± 44	51 ± 39
528	Stomach	207	56	216 ± 37	49 ± 12
	Dist jejunum	150	11	123 ± 23	63 ± 36
	Ileum	224	8[a]	188 ± 28	21 ± 3
530	Stomach	126	113[b]	99 ± 18	75 ± 18
	Ileum	128	15[a]	153 ± 48	23 ± 4
533	Dist jejunum	205	16[a]	171 ± 39	21 ± 2

[a]Model value more than two standard deviations below in vivo mean estimate.
[b]Model value more than two standard deviations above in vivo mean estimate.

to other insoluble dietary fibers, with minor adjustment of parameters to accommodate differences in fiber ion-exchange capacity, ion affinity, and hydration (if total ion content is to be estimated).

With the help of the model, a few conclusions can be drawn about the potential impact of corn bran fiber on mineral absorption. Focusing on Ca^{2+}, the ion of most nutritional interest of the minerals considered in this study, the pig diet (not mineral supplemented) contained 40 μmol/g Ca^{2+} and 10% by weight corn bran. The Ca^{2+} binding capacity of the corn bran is 106 μmol/g. Thus, of the Ca^{2+} supplied by the diet (the GI tract supplies some Ca^{2+} as well), the corn bran could bind 25% at most. For the small intestine ionic conditions given in *Table 1*, the range of model-estimated bran-bound Ca^{2+} was 5–35 μmol/g, or approximately 5–33% of total capacity. Therefore, corn bran may diminish total dietary Ca^{2+} availability by 1–8% in the upper GI tract. Fermentation of the bran and absorption of Ca^{2+} in the large intestine may further mitigate the influence of corn bran.[15] The Ca^{2+} content of the corn bran in the feed was approximately 5 μmol/g.[27] Thus the bran component of the diet is not a net contributor to the pool of available Ca^{2+}. The model-estimated small impact of corn bran on Ca^{2+} absorption is consistent with feeding studies, which have shown corn bran has a negligible influence on Ca^{2+} balance.[38] The impact of other potential dietary fiber sources with greater ion exchange capacities,[17] and at higher levels of dietary incorporation, may not be as innocuous. James et al.[15] drew a similar conclusion based on a survey of a variety of dietary fibers and the large fiber intake associated with human vegetarian diets.

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