Transport and recycling of radiocesium in the alimentary tract of reindeer

Hans Staaland[1], Knut Hove[2] and Øyvind Pedersen[1]

[1]Department of Zoology, Agricultural University of Norway, 1432 Aas-NLH, Norway.
[2]Department of Animal Science, Agricultural University of Norway, 1432 Aas-NLH, Norway.

Abstract: Transport of radiocesium between the body pools and the alimentary tract was studied in 7 reindeer calves. Comparisons were made between reindeer receiving the Cs- binder Prussian blue (Ammonium-ironhexacyanoferrate) and untreated animals.

The calves were fed lichens contaminated with ^{134}Cs + ^{137}Cs from the Chernobyl accident (about 10 kBq/day) for 4 weeks. Absorption and secretion of radiocesium, Na and K in the alimentary tract were calculated using ^{51}Cr-EDTA as a reference substance. Thirteen sections ofi the alimentary tract were sampled and analysed for radionuclides and chemical composition. In 4 animals, feeding with contaminated lichens continued until they were slaughtered, whereas in the 3 others the lichen feeding terminated 4 days before slaughter.

The activity concentration of Cs nuclides increased 5-17 - fold from duodenum to the distal colon, whereas the concentration of Na decreased and K remained almost constant. Radiocesium, Na and K were secreted into the rumen, the omasum and the abomasum, whereas Na and K also were secreted into the proximal small intestine. Prussian blue had no effect on Na and K recycling, but the flow of radiocesium from the abomasum to the anus and the fecal excretion increased markedly. In the 3 animals where feeding with contaminated lichens was disconutinued 4 days before slaughter, endogenous Cs was continuously recycled between the body pools and the alimentary tract. The net exchange of radiocesium between body pools and the alimentary tract was more than 4 times the amount ingested when lichens were fed. It is concluded that radiocesium is rapidly recycled between the alimentary tract and the other body pools. Cs-binders like ammonium-ironhexacyanoferrate may bind both endogenous Cs and Cs from feed.

Key words: Absorbtion, secretion

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Introduction

Reindeer require relatively large areas of plant growth to cover their energy requirements, and were therefore particulary susceptible to the airborne pollution of radiocesium from the Chernobyl accident. Radiocesium enters biological systems rapidly and is assumed to distribute in plant and animal tissues much like K. Within the reindeer body Na and K recycles rapidly between the alimentary tract and the other body pools (White *et al.* 1984. Staaland *et al.* 1986). As an alkali metal, Cs may be assumed to behave in a similar fashion, allowing an equilibration of endogenous Cs with freshly ingested Cs in the alimentary tract. Cesium binders of both the clay mineral (bentonite) and Prussian blue type (ammonium-ironhexacyanoferrates) have been used to reduce the radiocesium burden in farm animals an in domestic reindeer after the Chernobyl accident. Part of their effectiveness has been attributed to a possible binding of radiocesium which recycles from the body to the alimentary tract.

The biological half life of total body radiocesium is about 3 weeks in roe deer (Molzahn *et al.*1987), 1-3 weeks in reindeer (Holleman and Luick 1975) and 2-4 weeks in sheep and cattle (Howard *et al.* 1987; Goldman *et al.* 1965; Sansom 1966). Whole body estimates of Cs turnover do not, however, give information about cycling of radiocesium between the different cesium pools in the organism.

The purpose of the present paper is to study the patterns of secretion and absorption of radiocesium along the gastrointestinal tract of reindeer, and to locate the parts of the tract of interest for the binding of radiocesium to Prussian blue.

Material and methods

Seven male reindeer calves, 8-10 months old, were used. The animals were obtained from semidomestic herds in Southern Norway, and brought to the Agricultural University of Norway in September and November 1986. The reindeer were kept indoors (10°C) tied to their cribs from the time of arrival until slaughter. A commercial pelleted reindeer feed, RF71 with 4 percent $NaHCO_3$ added as a buffer, was used as the basic feed (Jacobsen and Skjenneberg 1979). In addition, the reindeer received lichens and at intervals some grass silage. The animals were fed twice a day. Before slaughter the body loads of ^{134}Cs + ^{137}Cs were brought up to 1-2 kBq/kg muscle tissue by feeding the animal about 320 g lichen DM/d for 4 weeks.

The lichens were collected in the Jotunheimen area of Southern Norway and were contaminated with radiocesium from the Chernobyl accident. The daily intake of ^{134}Cs + ^{137}Cs was about 9.9 kBq. In addition, 1 kg RF71 was given. The animals were divided into 3 groups. In 2 groups (I and II, Table 1) feeding with lichens continued until slaughter whereas in the

Table 1. Experimental design, feeding and treatments with ammonium-iron (III) hexcyanoferrate (II) (AFCF) and ^{51}CrEDTA. The treatments were carried out for 4 days prior to slaughter.

			Feed intake							
Group No.	Anim. No.	BW kg	Lichens g/d	RF 71 g/d	Total g/d	AFCF mg/d	^{51}CrEDTA kBq/d	$^{134}Cs+^{137}Cs$ kBq/d	Na mmol/d	K mmol/d
I	653	54.5	319	880	1199	0	329	9.9	486	221
	1003	52.0	319	880	1199	0	329	9.9	486	221
II	831	47.0	319	880	1199	500	329	9.9	486	221
	15	38.5	319	880	1199	500	329	9.9	486	221
III	195	55.0	0	998	998	525	218	0	548	244
	11	49.5	0	998	998	525	218	0	548	244
	34	51.5	0	567	567	525	218	0	311	138

third group (III) the reindeer were fed RF71 only for 4 days prior to slaughter.

All animals were given ^{51}CrEDTA sprayed on the feed for 4 days before slaughter. Equal doses of ^{51}CrEDTA were given at 08.00, 16.00 and at 23.00 (Table 1). Group III were given 500 mg/d Ammonium-iron (III) hexacyanoferrate (II) (AFCF, Riedel de Haen, West Germany) commonly known as Prussian blue, sprayed on the morning meal. The group III animals received the daily dose of AFCF divided in equal parts sprayed on RF71 together with ^{51}CrEDTA and given 3 times per day.

On the fourth day all animals were killed by a shot in the head. Muscle samples for determination of radiocesium activity were taken from the hind leg. The whole gastrointestinal tract was immediately removed and divided into 13 different sections: (Fig. 1): rumen, reticulum, omasum, abomasum, small intestine (3 sections), caecum, proximal colon, spiral colon (2 sections) and distal colon (2 sections). The content in each section was weighed and samples for chemical analyses and measurements of radioisotopes were kept frozen until analyzed. Also samples of food were kept frozen and analysed for chemical composition and content of radioisotopes.

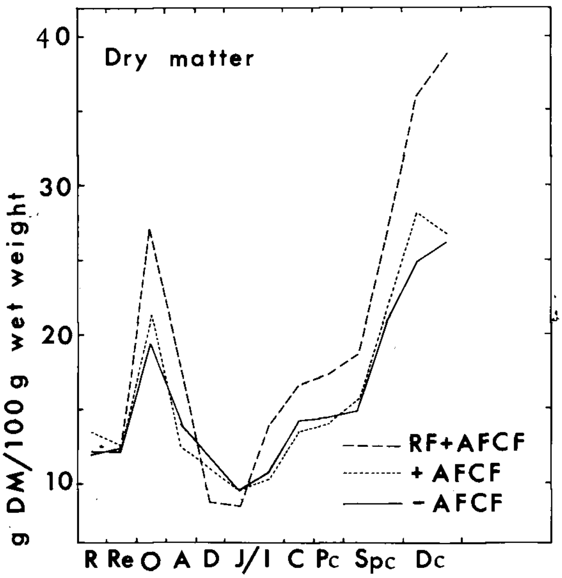

Fig. 1. Concentrations of dry matter along the alimentary tract of reindeer fed different diets and with and without treatment with Ammonium-ironhexcyanoferrate (AFCF); RF fed RF71 and given 525 mg AFCF/d (n=3); +AFCF fed lichens and RF71 and given 500 mg AFCF/d (n=2); -AFCF fed lichens and RF71 (n=2). R, rumen; Re, reticulum; O, omasum; A, abomasum; D, duodenum; J/I, jejunum/ileum; C, caecum; Pc, proximal colon; Spc, spiral colon; D, distal colon.

The activity of ^{134}Cs,^{137}Cs and ^{51}Cr in digesta food and muscle samples (300 g) were measured in 200 ml plastic vials using a Germanium detector connected to a Canberra 85 Multichannel Analyzer at the Isotope laboratory of the Agricultural University.

Alimentary contents and feeds were dried at 105°C for 24 hrs to determine dry matter content. The residues after ashing (625°C for 12 hrs) were dissolved in hydrochloric acid and diluted. Na and K were determined by atomic absorption spectrophotometry.

Samples of saliva were collected as previously described (Staaland *et al.* 1980). Na and K in saliva were determined by flame photometry and the content of radioactive Cs was measured in 5 ml samples in a LKB Wallac 1280 Ultrogamma Scintillation counter equipped with a 3 inch sodium- iodide detector.

The data were analysed by a model which assumes that a constant amount of ^{51}CrEDTA flows through each section of the intestine per day.

Based on the measurements of ^{51}CrEDTA concentrations into each section (M_i), and assuming that the ^{51}CrEDTA entry (M) into each section equals the amount ingested per day, the volume of wet mattter (M/M_i) per day passing through each section can be calculated. The amounts of ions, e.g. Na, K or radiocesium, leaving each section is calculated from this flow rate and local concentrations (C_i) (White *et al.* 1984).

The secretion or absorption in each section of the alimentary tract is thus the difference between flow into and flow out of the segment. Starting with the rumen, the net absorption or secretion is equal to the difference between nutrient or minerals in the food (Fo) and flow out of rumen. The sum of absorption or secretion in rumen/reticulum is the difference between food intake and flow out of reticulum. Similar calculations were carried out for each section of the alimentary tract. The cumulative exchange ($CABS_i$) therefore sums up the cumulative absorption or secretion from rumen through section i (i=1-13) of the alimentary tract Eq.1.

$$\text{Eq.1. } CABS_i = Fo - (M/M_i) * C_i$$

To visualize the activity of each site, the cumulative exchange ($CABS_i$) of Na, K and radiocesium between ingesta and body of the reindeer for each successive compartment were plotted graphically against the position of the compartment in the alimentary tract. This graph gives a visual documentation of cumulative exchange, i.e. absorption or secretion, of each element in each compartment of the tract. The approach is very sensitive to site-specific changes in nutrient exchange. The difference $CABS_{i-1}$-$CABS_i$, which can be read from the diagrams, gives the net secretion or absorption in each section.

Results

At the time of slaughter the combined concentrations of ^{134}Cs and ^{137}Cs in muscle tissues ranged from 822-2012 Bq/kg wet weight, whereas salivary activity was from 26-539 Bq/l (Table 2). Mean salivary concentrations of Na and K were 71 ± 25 and 11 ± 7 mmol/l. In the rumen and reticulum the dry matter content of ingesta was similar on all diets, whereas in the distal part of the alimentary tract animals fed a pure RF71 diet had a higher dry matter percentage than those fed a mixed RF71/lichen diet. No effect of treatment with AFCF on dry matter content was apparent (Fig. 1). The concentration of ^{51}Cr declined from the rumen/-reticulum to the abomasum and proximal small intestine. From then on a steady increase to the rectum was observed (Fig. 2). The combined activity of ^{134}Cs and ^{137}Cs followed basically the same pattern, except that an increase in acitvity was found in the omasum. The concentration gradient of ^{134}Cs + ^{137}Cs differed from that of Na and K (Fig. 2). Within the alimentary tract the stomachs dominated as the major pool for radionuclides and Na and K as well as water and dry matter (Table 3). However, relatively more of the total gastrointestinal pools of radionuclides than of Na, K, water and total digesta were found in the large intestine.

Table 2. Radiocesium in muscle tissue (Bq/kg wet weight) and in saliva (Bq/l) at the time of slaughter.

Group No.	Animal No.	Muscle	Saliva
I	653	1287	539
	1003	1806	x
II	831	822	159
	15	1285	119
III	195	1093	26
	11	1240	86
	34	2012	64

[x] Sample contaminated.

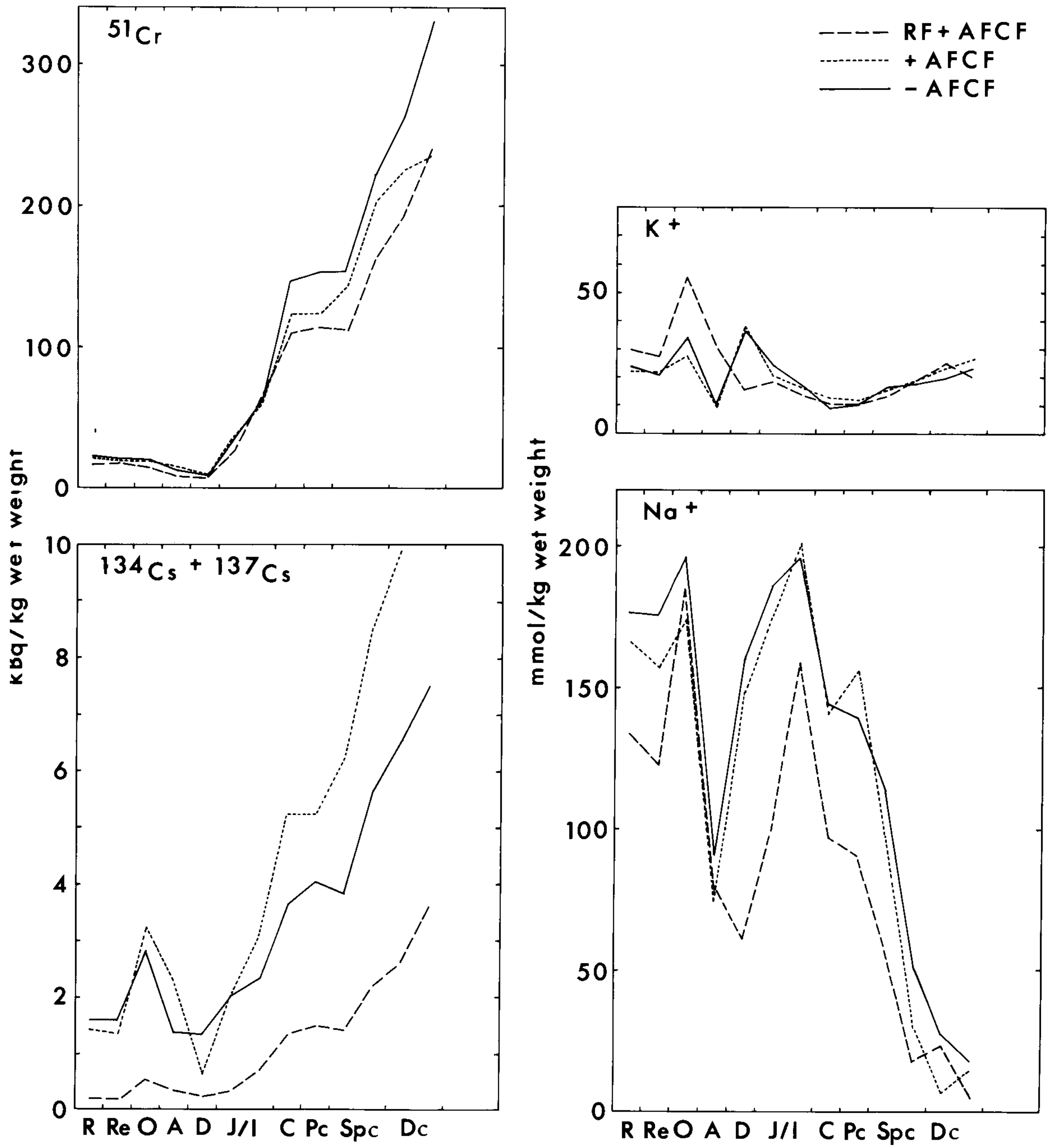

Fig. 2. Mean concentrations of ^{51}CrEDTA, ^{134}Cs + ^{137}Cs, Na and K along the alimentary tract of reindeer fed different diets and with or without treatment with (AFCF). Abbreviations are given in Fig. 1.

The total pool of radiocesium in the alimentary tract for those animals continuously fed contaminated lichens exceeded that in the daily feed by 4.7 and 6.6 kBq in groups I and II, wheras alimentary ^{51}CrEDTA was 88, 90 and 124% of daily intake in groups I-III respectively (Tables 1 and 3). Patterns of absorption and secretion along the alimentary tract were calculated according to descriptions given above and White *et al.*(1984) (Fig. 3). The diagrams (as decribed above) express the cumulative absorption and secretion in relation to the amounts

Table 3. Distribution of material in the alimentary tract of reindeer (average and standard deviation). Group 1: Fed lichens and RF71, Group II: Fed lichens and RF71 and given AFCF, Group III:Fed RF71 and given AFCF. For further explanations see Table 1.

	Total alim. pool size			Stomach (% of total)			Small int. (% of total)			Large int. (% of total)		
Group No.	1	II	III	I	II	III	I	II	III	I	II	III
n	2	2	3	2	2	3	2	2	3	2	2	3
Total content (kg)	7.8	8.4	104 ± 1.2	83.1	85.1	88.4 ± 8.0	7.6	7.0	5.6 ± 0.8	9.3	8.0	6.0
Water (kg)	6.8	7.3	9.4 ± 1.5	83.3	85.1	86.6 ± 1.0	7.7	7.2	5.6 ± 1.1	9.0	7.7	7.8 ± 2.0
Na (mmol)	1324.6	1328.8	1341.4 ± 269.3	84.8	86.0	90.6 ± 1.9	8.4	8.1	5.8 ± 1.1	6.8	5.8	3.6 ± 0.8
K (mmol)	170.5	177.3	291.3 ± 39.3	87.4	87.8	94.2 ± 1.0	7.8	6.7	3.0 ± 0.4	4.8	5.5	2.8 ± 0.6
$^{134}Cs+^{137}Cs$ (kBq)	14.6	16.5	3.0 ± 1.2	70.9	67.2	55.7 ± 4.7	8.3	8.3	11.2 ± 1.7	20.8	24.5	33.1 ± 4.7
^{51}Cr (kBq)	295.2	289.7	268.8 ± 10.4	49.3	57.9	60.5 ± 4.3	9.6	9.1	10.4 ± 1.4	41.2	33.0	29.1 ± 3.1

ingested. Values above the zero line show a net absorption relative to the amounts in the feed, and values below the line a net secretion. Negative slopes on the curve show secretion into the gastrointestinal tract whereas positive slopes shows absorption. From the diagrams it therefore appeared that radiocesium was secreted into the rumen/reticulum and apparently also into the omasum and abomasum. Absorption mainly took place in the small intestine. The absorption was less efficent when the animals were given AFCF (Fig. 3).

Similar patterns were observed for Na and K, but these elements were also secreted into the duodenum in large quantities. No effect of AFCF on absorption of these elements was detected.

Irrespective of diet or treatment with AFCF, the larger part of radiocesium flowing out of abomasum (67-80%) was absorbed in the intestines (Table 4).

Discussion

The alkali metals Na and K are rapidly recycled between the body pools and the gastrointestinal tract. The exchangeable pool of Na in the reindeer was about 60 mmol/kg BW (Staaland *et al.* 1982). The exchangeable pool of a reindeer weighing 50 kg (Table 1) would therefore be about 3000 mmoles. In the present study, as a consequence of the buffer in the RF71, the daily intake of Na was high (500 mmol). Nevertheless it appeared (Fig. 3) that the net daily exchange of Na between the gastrointestinal tract and the tissues was of the same order of magnitude as the total exchangeable body pool and by far exceeded the daily amount in food. The total body burden of ^{134}Cs + ^{137}Cs was not measured. However, Holleman *et al.*(1971), found that 78.9% of Cs body burden was located to the skeletal muscles, and muscles constituted 40.7% of the total body weight. Using their estimates, the

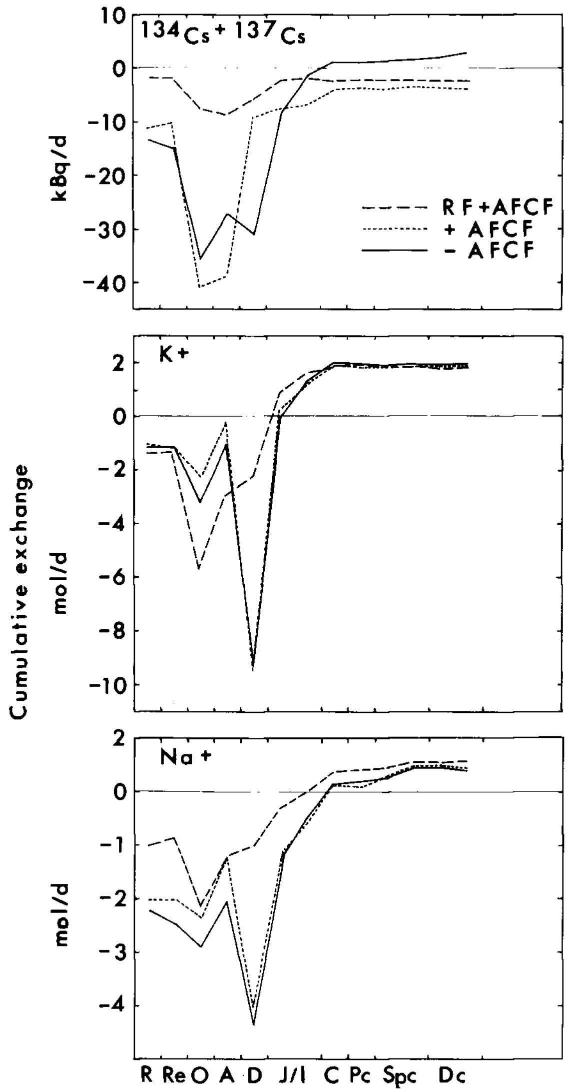

Fig. 3. Cumulative absorptions of radiocesium, Na and K in the alimentary tract of reindeer fed defferent diets and with and without treatment with AFCF. Negative changes indicate secretion and positive changes indicate absorption. Calculations for each element are made in relation to respective dietary intakes. Abbreviations are given in Fig. 1. For further explanations see text.

average body burden of radiocesium in our animals would be about 35 kBq. In the lichen-fed animals the daily flow of radiocesium out of the abomasum was 40-50 kBq, indicating a secretion of at least 30 kBq/d (Fig. 3, Table 4). The magnitude of net radiocesium exchange per day between the alimentary tract and the body therefore apppeares to be of the same order of magnitude as the total body pool of the animal.

After 4 days of feeding with only concentrate, the amount leaving the abomasum had declined to about 9 kBq/d, indicating a drastic reduction in the rate of radiocesium secretion to the upper gastrointestinal tract. A possible explanation of this may be a rapid decrease in the most readily available pools of radiocesium (Extracellular fluid and tissues with a rapid turnover of potassium). The present experiment does not allow us to draw any conclusions as to where this depletion occured.

The large recycling of alkali minerals, including Cs, contrasts to finding for bivalent and trivalent ions like Ca, Mg and P (White *et al.* 1984, Staaland *et al.* 1986). For these minerals small fractions only of the body pools seemed to be involved in exchange with the contents of the gastrointestinal tract.

Between radioactive Cs and Na and K there were differences with respect to the sits in the gastrointestinal tract where absorptions or secretions took place. All elements were secreted into the rumen/reticulum (Fig. 3). A major contribution is through saliva because of high concentrations and large volumes of saliva in ruminants (Table 3).

In addition, there was a large net secretion into the proximal small intestine of Na and K, whereas radioactive Cs apparently was secreted into the omasum and abomasum.

The method of slaughtering animals and the use of a non-absorbed marker to calculate absorption and secretion patterns in the gastronintestinal tract may not, however, be applicable in the omasum. Here, this method is most likely invalidated because of the preferential movement of the liquid phase of the ingesta through this organ (Engelhardt and Hauffe 1975, Faichney 1975, White *et al.* 1984). Irrespective of these errors there was an apparent large flow of radioactive Cs from abo-

Table 4. Nutrient flow and mean digestion of alkali elements in the alimentary tract of reindeer ± S.D. Group I: lichens and RF71; Group II: lichens and RF71 and given AFCF; Group III: RF71 and given AFCF. For further explanations see Table 1.

	Na			K			$^{134}Cs+^{137}Cs$		
Group No.	I	II	III	I	II	III	I	II	III
n	2	2	3	2	2	3	2	2	3
Intake (MMol/d or Bq/d)	4861	486	469 ± 137	221	221	209 ± 61	9876	9876	0
Leaving abomasum (mmol/d or Bq/d)	2605	1777	1818 ± 391	334	243	494 ± 70	37203	49008	8857 ± 7020
Leaving ileum (mmol/d or Bq/d)	1025	1126	540 ± 99	88	88	49 ± 9	12128	17108	2396 ± 629
Fecal output (mmol/d or Bq/d)	19	33	9 ± 15	23	35	21 ± 8	7522	14098	2953 ± 1344
Net absorption (mmole/d or Bq/d)	467	463	539 ± 15	198	186	188 ± 57	2354	-4222	-2953 ± 1344
Mean apparent dig. (% of intake)	96	95	98 ± 3	89	85	90 ± 1	24	-43	—

masum to duodenum (Table 4). Absorbtion of Cs and K seemed to be completed when the digesta reached the caecum, whereas Na also was absorbed in the large intestine (Fig. 3). There were also marked differences in absorption and secretion patterns between feeding regimens. The animal fed only the pelleted rations had secretion and absorption patterns in the proximal part of the intestine which differed from those also receiving lichens in the diet. These findings agree with previous studies (White *et al.*1984, Staaland *et al.*1986).

In the present study a close connection between the secretion of Cs and K was not apparent in the gastrointestinal tract since Cs mostly seemed to be recycled into the stomachs and K into the small intestine. In provious studies, Holleman and Luick (1975) observed reduced biological half life for Cs in reindeer in early summer. They explained this observation by increased intake of K from new growth of green vegetation in spring. A reduction in body retention of Cs has also been observed in rats following a very high increase in the intake/l of K (Wassermann and Comar 1961), but the effect of adding K to the diet of naturally Cs contaminated sheep was negligible (Hove and Ekern 1988). Further studies are therefore needed to explain the relationship between K and Cs excretion in animals.

The stochiometry of the chemical reaction between radiocesium and AFCF is not known since the concentrations of cold Cs in the digesta were unknown. However, the reaction seemed to be specific in the alimentary tract since there apparently was no effect of AFCF on the other alkali elements. According to our findings, the main function of the Cs binder is to inrease the alimentary flow of radioactive Cs by keeping Cs bound to a large molecule that cannot absorbed (Table 4). The increased flow rate is mainly achieved in the proximal part of the gastrointestinal tract and is maintained throughout the small and large intestine to the rectum (Fig. 3).

The large flow of radiocesium measured by the present method must to some degree represent a rapid recycling between the plasma pools and the gastrointestinal contents. Intracellular radiocesium shows a half life which is by no means compatible with the high gastrointestinal fluxes of radiocesium. It may therefore be expected that the fraction of the total body pool avilable for exchange with radiocesium will be rapidly reduced after a few days of treatment with AFCF or other cesium binders.

In the distal part of the alimentary tract very little Cs was secreted or absorbed. The addition of AFCF to the feed during the last 4 days before slaughter enabled the animals to greatly increase their fecal output of radiocesium. The negative net absorption in Table 4 showed that AFCF actually was instrumental in reducing the body burden of radiocesium during lichen feeding.

The effect of AFCF on radiocesium seems therefore to be an increased flow through the alimentary tract and increased rectal flow during AFCF administration. AFCF apparently binds part of the radiocesium in the stomach and keeps this element bound through the alimentary tract and thus prevents its absorption. This again cause a net fecal loss instead of a net absorption of radiocesium from the alimentary tract.

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