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Investigating the Partitioning of Inorganic Elements Consumed by Humans between the Various Fractions of Human Wastes – An Alternative Approach

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ABSTRACT

The elemental composition of food consumed by astronauts is well defined. The major elements carbon, hydrogen, oxygen, nitrogen and sulfur are taken up in large amounts and these are often associated with the organic fraction (carbohydrates, proteins, fats etc) of human tissue. On the other hand, a number of the elements are located in the extracellular fluids and can be accounted for in the liquid and solid waste fraction of humans. These elements fall into three major categories – cationic macroelements (e.g. Ca, K, Na, Mg and Si), anionic macroelements (e.g. P, S and Cl and17 essential microelements, (e.g. Fe, Mn, Cr, Co, Cu, Zn, Se and Sr). When provided in the recommended concentrations to an adult healthy human, these elements should not normally accumulate in humans and will eventually be excreted in the different human wastes. Knowledge of the partitioning of these elements between the different human waste fractions is important in understanding (a) developing waste separation technologies, (b) decision-making on how these elements can be recovered for reuse in space habitats, and (c) to developing the processors for waste management. Though considerable literature exists on these elements, there is a lack of understanding and often conflicting data. Two major reasons for these problems include the lack of controlled experimental protocols and the inherently large variations between human subjects (Parker and Gallagher, 1988) We have used the existing knowledge of human nutrition and waste from the available literature and NASA documentation to build towards a consensus to typify and chemically characterize the various human wastes. It is our belief, that this could be a building block towards integrating a human life support and waste processing in a closed system.

INTRODUCTION

In a healthy adult, one would expect the intake of elements to be equal to the output in the form of human wastes (feces, urine, respiration, sweat, semen and menstrual fluid). Schroeder (1973) reports "The body has marvelously exact mechanisms for maintaining homeostasis of inorganic elements. Unfortunately it has relatively poor mechanisms for maintaining the organic elemental content of the carbon, hydrogen and oxygen which is built up and deposited as fat". There are well-established reports that have defined calcium and phosphate homeostasis, based on the understanding of these processes [3, 11]. Wastes in healthy humans are well characterized by human physiological processes such as defined absorption rates of elements at the intestinal level, defined elemental transfer and mobilization at the kidney and sweat functions. Despite this assumption, the authors are not aware of reports to demonstrate this partitioning empirically.

An excellent study of input/output mass metabolic rates (MMR) was presented in the form of a computer simulation model to predict mass of urine and feces produced in a closed system[4]. The paper demonstrated that both feces and urine production were functions of Energy expenditure rate (EER) which in turn was a function of the input/output MMR. This paper made an assumption that the solid feces mass flow rate is some production ratio (dfs) of the dry food input and liquid feces mass flow rate as being dependent on the total water input.

Using the dry food input and liquid input, they were able to predict both solid and liquid fecal rates at different EER's.

They carried out similar studies to estimate liquid urine and solid urine outputs as a function of EER.

Our attempt will be to use physiological knowledge to predict elemental output. Further, if combined with the massflow output rate, one could establish solid and liquid waste generation rates as a function of human metabolic rate; dry food input rate and the fluid intake rate in a closed system.

ELEMENTAL COMPOSITION OF HUMANS

Oxygen, carbon and hydrogen are the predominant elements in humans and on an average dry weight basis comprise 65%, 18% and 10% respectively. The balance 7% of the weight is made up of inorganic elements. Nitrogen and sulfur though found in small amounts are often associated with the organic fraction. Of the more than 100 known elements, only 23 are essential for life. Of the other elements some such as Ca and P contribute to structural features in humans and hence not commonly found in soluble form, while others such as Na and K are found in soluble forms.

The variability that exists is shown in Table 1. Though generally, the high and low values that exist are within a range of +/1 50%, exceptions do occur as in the case of sodium where the range can be very high. The variations are the result of a number of factors (physiology, input rates, health of adult etc).

Table 1 shows the range of total elemental composition of the major inorganic elements in a 70Kg-humans – all values are in g/70 Kg person [2, 5, 6, 7, 9, 13]

	K	Mg	Ca	Na	P	S	Total N
High	245	35	1500	225	1200	310	3600
Low	135	21	800	800	.800	180	1800

	Fe	Mn	Zn	Cu	Mo	Co
High	3	0.020	2.30	0.14	0.12	0.003
Low	2	0.006	0.45	0.07	0.03	0.002

RECOMMENDED DAILY REQUIREMENTS (RDA'S)

RDA's are well quoted values and they are based on a number of studies. Typically, the RDA values are defined as the "standards to serve for good nutrition". They are constantly being revised and often vary with age groups. Though the numbers are based on numerous scientific grounds, in general they do tend to be between 0.75-1.5% of the total elemental weight of a 70 kg-person. Table 2 also shows the safe uptake intake limits. For many of the trace elements, the safe limit is quite restricted, but for the major ions higher doses does not pose toxicity issues. For example, one may take up to 9 times potassium before any harmful effects are observed.

Table 2 shows the daily requirements judged to be adequate for healthy adult, the safe upper intake limits relative to RDA) and the daily intake expressed as a percentage of the total elemental composition of the person (Data from 1,7 & 14).

Nutrient	RDA (mg)	Safe Upper Intake Limits
K	2000	9 X
Mg	350	1 X
Ca	1200	2 X
Na	500	5 X
P	1200	2 X
Fe	15	5 X
Mn	2-5	1 X
Zn	15	1 X
Cu	1.5-3	1 X
Mo	0.075-0.250	1 X
Co	Needed only by vegetarian	?

ABSORPTION OF ELEMENTS IN THE DIGESTIVE SYSTEM OF HUMANS

The gastrointestinal system is the portal through which the nutritive substances, vitamins and elements enter the body. In a typical adult consuming 2000 mls of water daily in food, only 10% (200mls) is excreted in feces. The absorption and excretion of the different elements is determined varies and depends on the element of interest. For example, highly soluble elements such as sodium are almost completely absorbed, while others such as calcium and phosphate are less readily absorbed resulting in a larger fraction of the ingested calcium and phosphate being released in the feces. Table 3 shows the net absorption of nutrients in normal healthy adults on diets of mixtures of plant and animal foods [11].

Table 3 – Net absorption of inorganic elements in the gastrointestinal tract of healthy adult humans.

Element	% absorption
K	80-90
Mg	25-50
Ca	5-50
Na	95
P	50-60
Fe	5-15
Mn	>5
Zn	33
Cu	25
Mo	40-50
Co	>50
Carbohydrates, Proteins & Fat	>90

As evident, the absorption rates are predictable and within a narrow range in healthy adult humans. Further, since there is reliable information on the elemental input (based on the RDA or the analysis of the food provided), one could predict the partitioning of the different elements in the major waste components (feces and urine) of humans.

LARGE VARIATIONS IN RANGE OF ABSORPTIVE CAPACITY.

In some cases, example magnesium and calcium, the absorptive capacity has a broad range and this has important implications. Generally, this is observed with elements that have low solubility in water and in these cases, the absorptive capacity is concentration dependent. We have used calcium as an example below:

Calcium – typically 99% of the calcium in humans is found within the bone while 1% is found in the extracellular fluid. The recommended calcium intake is between 0.8-1.2 g, (about 1% of the total body content). Typically 5-10% is obtained from water and the rest from solid foods. The absorption efficiency varies inversely with dietary calcium intake. In addition, there is always endogenous fecal calcium of 0.1-0.2 g independent of any calcium content[11]. This endogenous fecal calcium release is particularly evident during fasting.

No calcium in food : fecal calcium = 0.1-0.2 g (Baseline)

Low (0.5) calcium in food – 50% absorption;
Hence fecal calcium content =(0.5*0.5) +Baseline
= 0.35-0.45

Since homeostatic mechanisms operate in human systems, a balance of between 0.05-0.15g calcium will be released.

High (1.0g) calcium in food – 30% absorption;
Using similar calculations as above,
Hence fecal calcium content =0.97- 1.04g

The amount of calcium in urine is also dependent on rates of intake. Data from has been used to recalculate the percentage partitioning of excreted calcium between urine and feces are shown in Table 4.

Table 4: Changes in partitioning of calcium excretion in feces and urine based on calcium intake rates (all values are in g/person/day)

LOW	INTAKE	HIGH	INTAKE
URINE	FECES	URINE	FECES
0.05-0.15	0.35-0.45	0.13-0.16	0.97-1.04

The above data shows that the urine calcium content (0.015-0.16g) did not change significantly despite the level calcium intake. However, doubling the calcium content from the low level to high intake level, resulted in 3 times higher calcium levels being excreted in the feces. This suggests that when individuals are provided excessive calcium over the RDA in the diet, a greater proportion of it get excreted in the feces.

Normally, amount of calcium excreted in sweat is negligible (15 mg/day). In Spaceflights, exceptions have been noted. During the Apollo-17 flight there was a disproportionate increase in the fecal calcium content and it was suggested that malabsorption may have occurred[12]. It has been suggested that calcium malabsorption can be influenced by microgravity conditions. Whether this increased fecal calcium content is the result of lowered absorptive capacity or loss (extrusion) into the intestinal system from the body is an unanswered question. There is no literature or information on whether microgravity affects the gastrointestinal absorption of other elements.

Potassium

Potassium is the third highest element in a human body (after calcium and phosphorous). An adult human has a mean body content of 245g potassium ions. Potassium is found mainly in the muscles (64%). The distribution of potassium between cells is very tightly controlled with only 1.5-2.5% being found in the extracellular fluid [1]. The major excretory route is through the urine through which 90% of the potassium is eliminated.

Phosphate

An adult human has a mean body content of 700 g phosphate ions. 85% of this element is found in bones. The RDA 1200 mg. Unlike, calcium, absorption is constant (60%) within the recommended range of 600-2000 mg, but at higher concentrations, the phosphate absorption is severely decreased, resulting in much of the phosphate being released in the feces. The absorbed phosphate is released through the urine stream.

Magnesium

An adult human has a mean body content of 28g magnesium ions. Fourty percent of this element is found muscles and soft tissues, 59% in the bone and 1% in the extracellular fluid[2]. Magnesium absorption is far less efficient than calcium. Similar to calcium it shows a concentration dependent absorption with rates of absorption being higher at lower feed concentrations.

Sodium

Typical sodium concentration can vary significantly even in healthy adults. However, sodium is almost completely absorbed and hence there is no sodium excreted in the feces, except during diarrhea [5, 9]. In general, all the sodium is excreted either through urine or sweat, with little or none being excreted in feces.

Typical Elemental Composition

Typical elemental levels reported in literature to-date are provided in Table 5. These values on columns 2 and 3 were taken from healthy adults but whose source of elemental input was often not known. The table is limited to only a few of the elements and particularly to those known to be considered important in resource recovery. A range of the partitioning ratios between the urine and feces based on these actual values are also provided. This type of information is important in identifying technologies for resource recovery. For example, the presence of high levels of sodium will clearly make using urine as a direct plant nutrient source, despite the high potassium cont.

Table 5 – Typical elemental composition of feces and urine reported in medical literature (all values are in g/person/day).

	Urine (g/day)	Feces (g/day)	Urine/Feces ratio (wt basis)
K	0.78-2.50	0.75-0.88	0.9-2.8
Ca	0.2-0.5	0.1-1.0	0.5-1.0
Na	3.45-4.53	Traces	Almost exclusively in urine
P	0.8-2.5	0.9-2.7	0.6-0.9
Fe	1.0	0.7-1.0	1.0
Mn	0.000001-0.00001	0.009-0.0024	0.0001-0.004
Zn	0.0003-0.0004	0.005-0.010	0.04-0.06
Cu	0.0001-0.0005	0.0015-0.0021	0.02-0.06
Mo	0.00001-0.00003	0.002-0.004	0.008-0.05
Total N	35	16	2.2

The data show some interesting patterns in distribution: (a) the trace elements are almost completely excreted in feces with no significant amounts being released in urine. (b) not surprisingly, two-thirds of the nitrogen is excreted through urine.

INPUT/OUTPUT ANALYSIS

The elemental composition of the food of astronauts is very well defined. Using a very simple equation, one could predict the partitioning and distribution of the different elements in the major human wastes, urine and feces.

Elemental Composition of Feces = (1-Ai)*DE + (Bi) +Ci

Where Ai – absorptive capacity of the intestine

DE = Elemental composition in the diet (this is a variable value and can either computed from laboratory data showing the individual elemental composition of the food consumed; alternatively it can be assumed that the humans are fed a standard diet to meet the RDA values – in such cases, the RDA values can be used for this variable number).

Bi = Endogenous fecal elemental output and which is a measure of the secretion from the extracellular fluidic component into the intestine (in the case of calcium, it is 0.1-0.2 g per day)

Ci = elemental composition in excess of the absorptive threshold value

Elemental Composition of Urine = (Ai *DE * Gi)

Where Gi = glomerular filtration efficiency – typically this value is around 95% under normal metabolic conditions in a healthy adult. Clearly, many other factors both human health and environmental conditions (e.g. microgravity conditions) which will change this value. Other human factors that can change this value are the metabolic rate and activity of the subject. As our quantitative knowledge of human physiology increases, we could incorporate the information into the database.

Table 6 (shown in the appendix) shows input/output analysis for a selected number of inorganic elements of importance to humans and in resource recovery/waste processing technologies.

CONCLUSIONS

This paper has used an alternative approach to characterizing and quantifying the elemental partitioning between the two major human wastes, feces and urine. Fundamentally, it uses the principle that if we do have knowledge of the inputs we could predict with reasonable certainty the output of the elements. It uses well proven human physiological data and knowledge to predict the elemental composition of these human wastes. In the light of the fact, that various limitations prevent the use of large amounts of human wastes, particularly feces and urine, this approach could provide a means for simulating the wastes from a chemical perspective. Once simulated, appropriately chemically developed simulate can be used in the waste processing technologies, as a first step. However, the authors do recognize that there are physical characteristics of the wastes that are not considered and that in the later developmental stages of the waste technology processors, it is likely that "real" wastes will need to be used.

This paper makes the assumptions that the subjects considered are healthy adults whose dietary inputs are highly controlled, which is justifiable for astronauts.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

RDA	Recommended dietary allowance
MMR	Mass metabolic rates
EER	Energy expenditure rate
DE	Dietary input (this is a variable value and can either be based on the RDA values or by actual laboratory measurements of the elemental composition of the foods consumed by humans)
Ai	Intestinal absorptive capacity
Bi	Endogenous Fecal Output
Ci	Elemental content in excess of absorptive capacity
Gi	Glomerular filtration efficiency

APPENDIX –

TABLE 6 - Partitioning of some major inorganic elements in human wastes as a function of nutrition input

(All values are in mg/person/day). The DE values used were the typical RDA mean values in a standard diet, but other values based on laboratory analysis of elements from a standard diet may also be used, if such data are available)

ELEMENT	DE	Ai	Bi	Ci	Gi	Feces	Urine	Other wastes
K	2000	0.95	0	0	0.95	100	1805	95
Ca	600	0.5	0.15	0	0.95	300.15	285	14.85
Na*	500	0.95	0	0	0	25	0	475
Mg	350	0.375	0	0	0.95	218.75	124.7	6.56
P	1200	0.55	0.2	0	0.95	540.2	627.0	32.80
Fe**	15	0.1	0	0	0.75	13.5	1.1	0.38
Mn	3.5	0.05	0	0	0.75	3.325	0.1	0.04
Zn	15	0.33	0	0	0.75	10.05	3.7	1.24
Cu	2	0.25	0	0	0.75	1.5	0.4	0.13

*No data has been found so far on excretion of sodium from the body into the gastrointestinal system. However, based on the intestinal membrane it would not be surprising if sodium is pumped into the gut.

** The kidney is not generally known to be good at filtering trace elements hence a lower value has been used for the trace elements. As more reliable data becomes available, the more reliable numbers will be inserted.