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SPECIAL ARTICLE

Fluid intake, renal solute load, and water balance in infancy

A simple, largely empiric method for estimating renal solute load is proposed. Utilizing this method, examples of urine concentration and water balance are described in hypothetic infants receiving various feedings at differing volumes of intake and with normal or increased extrarenal losses of fluid. Circumstances in which water balance must be a primary consideration in infant feeding are discussed.

This is an important paper. It is not for casual reading but will require study. The concepts enumerated should be understood and utilized by all physicians who are responsible for the medical care of children.

W. E. N.

Ekhard E. Ziegler, M.D.,* and Samuel J. Fomon, M.D.

IOWA CITY, IOWA

IMMEDIATE goals in infant feeding include provision of adequate intakes of water, total calories, and essential nutrients. In most instances, diets supplied to normal infants will include more than the required amounts of water, and it is therefore common for physicians and nutritionists to concern themselves with problems relating to intakes of calories and individual nutrients, assuming that the infant's water balance

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From the Department of Pediatrics, University of Iowa.

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Reprint address: Samuel J. Fomón, Department of Pediatrics, University Hospitals, Iowa City, Iowa 52240.

**Fellow of the Max Kade Foundation, New York.*

will be maintained. The purpose of this discussion is to consider circumstances in which water balance must be a primary consideration in infant feeding: (1) relatively low fluid intake, (2) greater than normal extrarenal losses of fluid, (3) low renal concentrating ability, and (4) consumption of a diet yielding a large renal solute load. The first 2 of these circumstances often coincide and, in such instances, the third and fourth conditions are particularly threatening.

ESTIMATE OF RENAL SOLUTE LOAD

Solutes that must be excreted in the urine are referred to collectively as the renal solute load. With rare exceptions, the main contributors to renal solute load will be nitrogenous substances and electrolytes. Sugars, a major component of dietary solutes, are ordinarily metabolized to carbon dioxide and water and therefore do not contribute to the renal solute load. For this reason, total solute concentration of an infant's diet has little predictive value with respect to renal solute load.

An estimate of renal solute load must be relatively simple if it is to be useful in pediatric practice. We propose that the estimate be based on dietary intake of nitrogen and of 3 major minerals—sodium, potassium, and chloride. For reasons discussed in the Appendix, each gram of dietary protein is considered to yield 4 mOsm. of renal solute load and each milliequivalent of sodium, potassium, and chloride is assumed to contribute 1 mOsm.

This estimate of renal solute load was developed primarily from data pertaining to infants fed whole cow milk or other feedings that yield relatively high renal solute loads. Under these circumstances, the fraction of dietary nitrogen and various electrolytes incorporated into newly synthesized body tissue or lost through skin is relatively small. When diets provide lesser amounts of protein and electrolytes, retention for growth and losses through skin constitute a larger fraction of the intake and our proposed calculation will overestimate the renal solute load. However, problems arising from overestimating the size of the renal solute load are of less clinical importance than are problems arising from underestimating it. In addition, knowledge of the size of the renal solute load is more important when the renal solute load is large than when it is small.

INTAKE OF WATER

Although milk and most milk formulas provide only about 88 ml. of preformed water per 100 Gm., an additional 8 ml. (approximately) of water will be derived from metabolism of protein, carbohydrate, and fat. It may therefore be assumed that volume of water available is approximately equal to volume of milk or formula consumed. We have also assumed that 100 Gm. of any commercially prepared strained or junior food will provide 100 ml. of water. In view of the high water content of most such foods, little error will be introduced by this assumption.

RELATION BETWEEN VOLUME CONSUMED, EXTRARENAL LOSSES, AND RENAL CONCENTRATING ABILITY

The examples presented in this and subsequent sections of the discussion concern fluid intake, extrarenal losses, and osmolar concentration of the urine of a hypothetic 4- or 5-month-old infant weighing 7 Kg. The infant is fed either 1,000 ml. or 750 ml. of whole cow milk; extrarenal losses of fluid are assumed to be 350 ml. (300 ml. from skin and lungs[1-5] and 50 ml. in feces[1-3, 5, 6]) when exposed to normal environmental temperature (Fig. 1, *A* and *C*) and 600 ml. (550 ml. from skin and lungs[2, 3, 7] and 50 ml. in feces*) when exposed to elevated environmental temperature (Fig. 1, *B* and *D*). As may be seen from Table I, estimated renal solute load arising from 1,000 ml. of whole cow milk is 221 mOsm. At normal environmental temperature (Fig. 1, *A*), the

*Increased fecal losses will be considered separately (see Diarrhea).

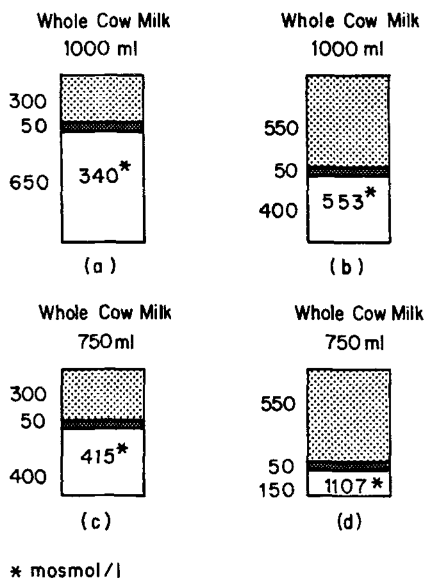

Fig. 1. Relation between volume consumed, extrarenal losses, and solute concentration of urine of hypothetic 7 Kg. infant fed 1,000 ml. (*a* and *b*) or 750 ml. (*c* and *d*) of whole cow milk. The upper stippled area of each column indicates the volume of losses from skin and lungs. The central, more densely stippled area indicates the volume of fecal loss (assumed in each instance to be 50 ml.). The unstippled lower segment of each column indicates the volume of water available for urinary excretion and the urine concentration that would result from excretion of the renal solute load in that volume of urine.

hypothetic infant consuming 1,000 ml. of milk has 650 ml. of water available for renal excretion of these solutes and urinary concentration is 340 mOsm. per liter. At elevated environmental temperature (Fig. 1, *B*), only 400 ml. of water are available for renal excretion and urine concentration is 553 mOsm. per liter. Since nearly all normal infants will be able to concentrate the urine to more than 553 mOsm. per liter,[1, 3, 5, 8-11] there is no threat to water balance.

It should be noted that the assumed value (550 ml.) for losses of water from skin and lungs at elevated environmental temperature is by no means extreme. Several reports[2, 3, 12] have documented situations in which water losses through skin and lungs were greater.*

*For the sake of simplicity we have chosen to ignore observations[2, 8] suggesting that during heat stress there may be some tendency toward retention of electrolytes.

Fever increases water losses through skin and lungs, probably to a lesser extent than does elevated environmental temperature; however, the literature provides little basis for quantitative estimation of the effect of fever. Using the commonly employed estimate of a 10 per cent rise in evaporative water loss per degree centigrade rise in body temperature, one would calculate evaporative losses of 420 ml. per day for an elevation of body temperature of 4° C.

If intake of cow milk is decreased to 750 ml., renal solute load will be decreased proportionately (221 mOsm. per liter × 0.750 liters = 166 mOsm.). Since extrarenal water losses will be unchanged, at normal environmental temperature 166 mOsm. will be excreted in 400 ml. of available water (Fig. 1, *C*), resulting in urine concentration of 415 mOsm. per liter. It is apparent that *decrease in the amount of intake of a specified diet will ordinarily lead to increased concentration of the urine* (until the maximal concentrating ability has been reached).

If 750 ml. of cow milk are consumed in the presence of extrarenal losses of 600 ml. (Fig. 1, *D*), urine concentration would need to be 1,107 mOsm. per liter to maintain water balance. Many infants will be able to achieve a urine concentration of this degree, particularly when the ratio of urea to non-urea solutes in the urine is high.[5, 9] However, it is apparent from the literature[8, 10] that some otherwise normal infants are unable to concentrate the urine above 600 or 700 mOsm. per liter. With a specified diet (and therefore specified renal solute load), it is apparent that in this situation renal concentrating ability will determine how closely extrarenal losses may approach water intake before water balance will become negative. Fig. 2 concerns a hypothetic infant consuming 750 ml. of whole cow milk and with extrarenal losses of 600 ml. The examples chosen are similar to those in Fig. 1, *D* except that concentrating ability is limited to 1,000 mOsm. per liter or to 700 mOsm. per liter. Because of the limitation of renal concentrating ability, excretion of the renal solute load of 166 mOsm. cannot be ac-

Table I. Dietary intake of protein, sodium, chloride, and potassium and estimated renal solute load from various feedings

Feeding		*Dietary intake*				*Estimated renal solute load*		
		Protein (Gm.)	*Na (mEq.)*	*Cl (mEq.)*	*K (mEq.)*	*Urea* (mOsm.)*	*Na + Cl + K (mOsm.)*	*Total (mOsm.)*
Whole cow milk	1,000 ml.	33	25	29	35	132	89	221
Human milk	1,000 ml.	12	7	11	13	48	31	79
Strained pears	100 Gm.	0.3	0.2	0.2	1.6	1	2	3
Strained beef and vegetables	100 Gm.	6.5	13.3	10.6	3.7	26	28	54
Boiled skim milk	1,000 ml.	46	35	40	49	184	124	308

*Assumed to account for 70 per cent of nitrogen intake (see text).

complished in the 150 ml. of water available from the diet. Negative water balance will therefore result. The extent of the negative water balance will be small when renal concentrating ability is 1,000 mOsm. per liter (Fig. 2, *A*) and moderate when renal concentrating ability is 700 mOsm. per liter (Fig. 2, *B*).

FEEDING CHOICE

In the situation presented in Fig. 1, *A*, where 650 ml. of water was available for excretion of 221 mOsm. of renal solute load, an infant with chronic renal disease and urinary concentrating ability of 300 mOsm. per liter would be in negative water balance. However, if this infant were to receive 1,000 ml. of human milk instead of 1,000 ml. of whole cow milk, it would be necessary for him to excrete only 79 mOsm. (Table I) in 650 ml. of water and water balance would be easily maintained. One may therefore conclude that *whenever renal concentrating ability is severely limited, renal solute load is a primary consideration in choice of diet.*

Renal solute load presented by the diet should be a major consideration in choice of feeding, not only when renal concentrating ability is extremely limited but whenever volume of food consumed is low and/or extrarenal losses of fluid are high.

Low fluid intakes are particularly likely to be encountered in infants with severe congenital heart disease and in those with various neuromuscular diseases. Because of difficulties encountered in feeding such infants, it is frequently desirable to use for-

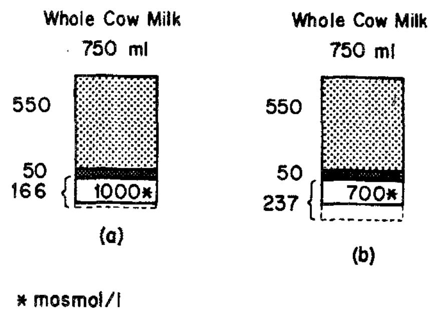

Fig. 2. Influence of renal concentrating ability of 1,000 mOsm. per liter *(a)* or 700 mOsm. per liter *(b)* on water balance of hypothetic infant with extrarenal losses of 600 ml. and dietary intake of 750 ml. of whole cow milk. Various areas of the columns have the same significance as in Fig. 1. The segment of the column outlined by interrupted lines indicates the extent of negative water balance.

mulas more concentrated than 67 Kcal per 100 ml. (20 Kcal per ounce). Clearly, it is possible to provide an adequate caloric intake in a low total fluid volume and this can be accomplished without increasing renal solute load. However, infants fed ad libitum appear to regulate food intake largely on the basis of caloric needs. Therefore, volume of food (and, consequently, fluid) ordinarily decreases as caloric concentration of the formula is increased,[13] and the margin between fluid intake and extrarenal losses may become small. For example, if an infant with extrarenal losses of 350 ml. per day (e.g., Fig. 1, *A* and *C*) ingested only 500 ml. per day, 150 ml. would be available for renal excretion. While this urinary volume would be adequate for excretion of a modest renal solute load, it is evident that even a slight

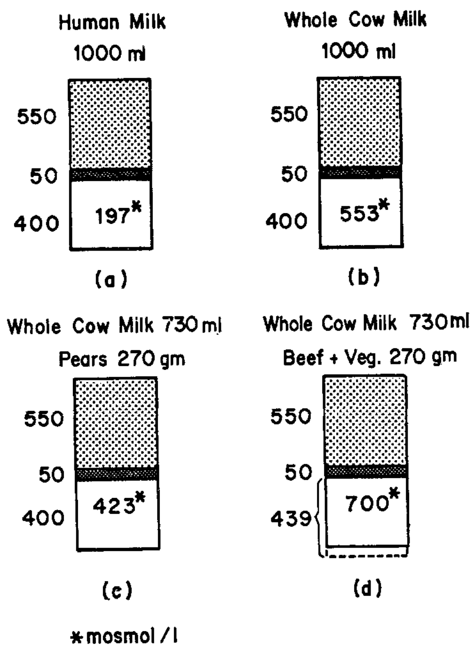

Fig. 3. Influence of various diets on urine concentration and water balance of hypothetic infant with extrarenal losses of 600 ml. Various areas of the columns have the same significance as in Figs. 1 and 2. (For discussion, see text.)

increase in extrarenal water losses would result in negative water balance. We have therefore adopted the general policy that *formulas should not be calorically concentrated above 100 Kcal per 100 ml. (30 Kcal per ounce)*. At this level of concentration it becomes important to avoid diets that present high renal solute loads: Protein should account for no more than 10 per cent of caloric intake and commercially prepared strained and junior baby foods with high salt content should be avoided. Furthermore, the diet should be altered promptly to one of lower caloric density when environmental temperature is elevated or in the presence of febrile illness, diarrhea, or other abnormal extrarenal water losses.

When high extrarenal water losses are combined with a diet yielding high renal solute load, water balance may be jeopardized even when normal volume of intake is maintained. Fig. 3 indicates the influence of choice of feeding on water balance of a hypothetic infant receiving approximately 1,000 ml. of fluid, with renal concentrating ability limited to 700 mOsm. per liter and with extrarenal fluid losses of 600 ml. When human milk is fed (Fig. 3, *A*), 79 mOsm. (Table I) will have to be excreted in 400 ml., resulting in urine concentration of 197 mOsm. per liter. The analogous situation in which cow milk is fed (Fig. 3, *B*) has already been presented (Fig. 1, *B*) and is included here merely for purposes of comparison.

Fig. 3, *C* and *D* concern the water balance of the same hypothetic infant when food intake instead of consisting of 1,000 ml. of milk consists of 730 ml. of milk and 2 jars (135 Gm. each) of commercially prepared strained baby food—one yielding a low renal solute load (pears) and one yielding a high renal solute load (beef and vegetables). The renal solute load from 730 ml. of whole cow milk is 161 mOsm. (221 mOsm. per liter × 0.730 liter). Renal solute load from 270 Gm. of strained pears (Table I) is only 8 mOsm. Thus renal solute load arising from the combination of cow milk and pears would be 169 mOsm., a lesser load than that presented by an approximately similar total volume of intake from cow milk alone. If, however, protein and electrolyte content of the strained food were high, total renal solute load might be substantially greater than that depicted in Fig. 3, *B*. In Fig. 3, *D* it is assumed that 270 Gm. of strained beef and vegetables is fed, presenting a renal solute load of 146 mOsm. Total renal solute of the diet would be 307 mOsm. and with renal concentrating ability limited to 700 mOsm. per liter, 439 ml. of urine would be required for excretion. The infant would therefore be in negative water balance.

Most commercially prepared formulas as well as cow milk with added carbohydrate will yield renal solute loads[14] that are considerably lower than that from whole cow milk, though greater than the renal solute load presented by human milk. The greater margin of safety provided by these feedings will be of little significance under most circumstances; nevertheless, it is apparent that a formula yielding relatively low renal solute load may be of advantage in situations such as those we have just discussed.

If fluid intake of an infant falls below extrarenal fluid losses, as may occur in severe anorexia or vomiting, renal solute load and renal concentrating ability will determine the size of the water deficit. Thus in management of situations involving fluid deficit, it seems reasonable to offer only fluids that yield as little renal solute load as possible until water balance has been restored.

DIARRHEA

When extrarenal losses of fluid are increased because of diarrhea, these losses are accompanied by fecal losses of solutes as well. Fig. 4 indicates the renal solute load and fluid balance of a hypothetic infant who is assumed to lose 300 ml. of diarrheal fluid[6, 12, 15] containing 45 mOsm. (150 mOsm. per liter[6, 12, 15-18]) of substances that would, if absorbed, contribute to renal solute load. Thus the renal solute load as calculated in the earlier examples would, in the presence of diarrhea, be decreased by 45 mOsm.

When 1,000 ml. of whole cow milk are consumed (Fig. 4, *A*), 176 mOsm. (221 − 45 = 176) will be excreted in a urine volume of 400 ml., resulting in urine concentration of 440 mOsm. per liter. Because boiled skim milk is still recommended by some physicians in management of diarrhea, Fig. 4, *B* has been included for comparison with Fig. 4, *A*. It is important to recognize that *per unit of volume, skim milk provides a slightly greater renal solute load than does whole milk, and solute concentration is further increased by loss of water during boiling.* We have assumed that skim milk after gentle boiling for 5 minutes will yield a renal solute load of 308 mOsm. per 1,000 ml. (Table I). With an intake of 1,000 ml. of boiled skim milk (Fig. 4, *B*) and fecal loss in diarrheal fluid of 45 mOsm. of potential renal solute load, there will remain 263 mOsm. to be excreted in 400 ml. of urine, resulting in urine concentration of 657 mOsm. per liter.

The inadvisability of using boiled skim milk in treatment of diarrhea can be demonstrated more dramatically by considering a hypothetic infant with moderately decreased volume of intake (750 ml.) and renal concentrating ability limited to 700 mOsm. per liter. Volumes of intake by infants with diarrhea are, in fact, often low.[18] Renal concentrating ability of such infants does not appear to be less than that of healthy infants[18] but, as already mentioned, renal concentrating ability of some otherwise normal infants is limited to 700 mOsm. per liter.

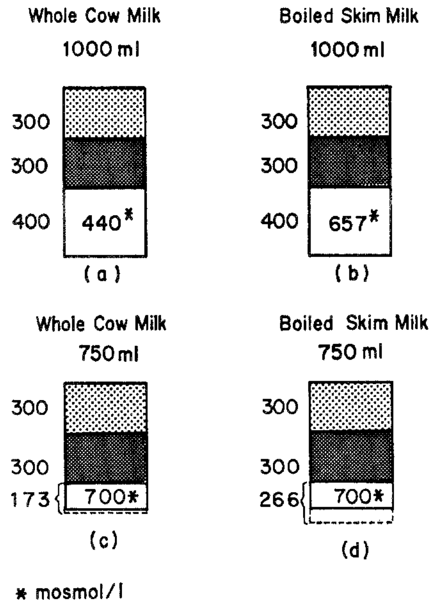

Fig. 4. Urine concentration and water balance of hypothetic infant with diarrhea fed 1,000 ml. or 750 ml. of whole cow milk or boiled skim milk. Various areas of the columns have the same significance as in Figs. 1 and 2. (For discussion, see text.)

Under these circumstances, feeding of whole milk (Fig. 4, *C*) will yield a renal solute load of 121 mOsm. (166 mOsm. of potential renal solute load provided by diet minus 45 mOsm. assumed to be lost in diarrheal fluid) and will require 173 ml. of urine for excretion, resulting in slightly negative water balance. Feeding of 750 ml. of boiled skim milk (Fig. 4, *D*), will yield a renal solute load of 186 mOsm. (231 mOsm. of potential renal solute load provided by diet minus 45 mOsm. assumed to be lost in diarrheal fluid) and require 266 ml. of urine for excretion. The magnitude of the negative water balance will therefore be considerably greater when boiled skim milk is fed than when whole milk is fed.

SUMMARY

Water balance must be a primary consideration in infant feeding when (1) fluid intake is low, (2) extrarenal losses of fluid are greater than normal, (3) renal concentrating ability is low, or (4) the diet yields a high renal solute load. Often, several of these conditions will exist concurrently.

To aid in evaluating the safety of various feedings in maintaining water balance, a simple, largely empiric method based on dietary intake is described for estimating the renal solute load. Utilizing this method, examples of urine concentration and water balance are described in hypothetic infants receiving various feedings at differing volumes of intake and with normal or increased extrarenal losses of fluid.

Because water is constantly lost through skin and lungs and in feces, solutes arising from the diet must be concentrated for renal excretion in only a fraction of the dietary water. The ratio of renal solute load to water available for renal excretion will increase when volume of intake of a feeding decreases. Therefore, decrease in the amount of intake of a specified food will ordinarily lead to increased concentration of the urine or, if maximal concentrating ability is reached, to negative water balance.

The possibility that such limitation of renal concentrating ability may be present should be kept in mind in evaluating the safety of feedings with respect to renal solute load. When insensible water loss is high, as in infants exposed to elevated environmental temperature, the relation between volume of intake, type of feeding, and renal concentrating ability will determine whether water balance can be maintained. It is emphasized that the renal solute loads presented by various milks and strained foods differ widely.

With feedings of high caloric density, volume of food (and, consequently, fluid) will ordinarily be relatively low, and it is therefore recommended that formulas be concentrated to no more than 100 Kcal per 100 ml. (30 Kcal per ounce). At formula concentrations approaching 100 Kcal per 100 ml., it is desirable to avoid feedings that present a high solute load for renal excretion.

Diets that yield a high renal solute load should not be fed to infants with diarrhea; for this reason, feeding of boiled skim milk is not recommended.

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APPENDIX

Presented here are comments on the manner in which we have arrived at our assumptions that each gram of dietary protein yields 4.0 mOsm. of potential renal solute load, and the sum of all dietary sodium, chloride, and potassium (expressed in millisomoles) provides a reasonable approximation of urinary excretion of all nonnitrogenous solutes. For reasons already mentioned, we have considered primarily the case of infants fed whole cow milk or diets containing similar quantities of protein and electrolytes. The first assumption rests on reasonably secure grounds. Few data are available to support the second assumption.

Nitrogen. When protein accounts for 20 per cent or more of caloric intake of normal infants, urinary excretion of nitrogen will generally account for 60 to 70 per cent of nitrogen intake.[19] Therefore in estimating renal solute load, we have assumed that 70 per cent of dietary nitrogen is excreted in the urine. Furthermore, urea, which contains 2 atoms of nitrogen per molecule (therefore, 28 mg. of urea nitrogen contribute 1 mOsm.), accounts for at lease 80 per cent of the nitrogen in the urine.[20-23] The remainder is composed mainly of compounds containing either one (e.g., ammonia, amino acids) or 3 or more (e.g., creatinine, uric acid) atoms of nitrogen. Thus one may assume that on the average each 28 mg. of urinary nitrogen contributes one milliosmole of renal solute load. Because one gram of protein contains 160 mg. of nitrogen, of which 70 per cent (112 mg.) is excreted in the urine, one gram of dietary protein is assumed to yield 4 mOsm. of renal solute load.

Electrolytes. A few observations reported in the literature[2, 3, 5] together with unpublished data from our metabolic unit indicate that combined urinary excretions of sodium, chloride, and potassium (in millisomoles) account for approximately 80 per cent of dietary intake of these minerals when infants are fed whole cow milk. Urinary excretion of phosphates (expressed as millisomoles) accounts for a renal solute load approximately 20 per cent as great as that made up by sodium, chloride, and potassium.[3, 24] Other nonnitrogenous urinary solutes are ordinarily of minor importance relative to sodium, chloride, potassium, and phosphates. Therefore, somewhat fortuitously, the sum of all dietary sodium, chloride, and potassium, provides a reasonable approximation of urinary excretion of all nonnitrogenous solutes.

As additional data become available on the relation between dietary intake and urinary excretion of sodium, chloride, potassium, and phosphate, more accurate predictions of renal solute load will become possible.