PROCEEDINGS OF THE SOCIETY FOR EXPERIMENTAL BIOLOGY AND MEDICINE **153**, 359-362 (1976)

Postnatal Changes of Water and Electrolytes of Rat Tissues (39545)

SIDNEY SOLOMON, PHYLLIS WISE, AND ALBERT RATNER

Department of Physiology, The University of New Mexico, School of Medicine, Albuquerque, New Mexico 87131

Electrolyte and water contents of neonatal tissues are different than those of mature animals. Cellular and extracellular water content is high, sodium content is relatively high, and potassium content is low (1-4). A detailed examination of water and electrolyte changes during development for tissues other than muscle (1, 3) and brain (4) has not been done. The purpose of this study was to determine whether water and electrolyte regulation mature at the same time during postnatal development in several tissues: heart, liver, kidney, spleen, ovary, and testis.

Methods. Young rats (Simonsen-Wistar, Gilroy, Calif.) were selected from litters raised in our animal quarters. Two males and two females were used at each time period studied. The only exception to this was that only one male and two females were analyzed at 60 days and only one of each sex at 100 days. The number of animals remaining in each litter was approximately the same in order to insure that growth rates were reasonably matched.

The animals were anesthetized with ether, the thorax was opened, the heart was removed, and the ventricles were separated, blotted, and weighed on aluminum tares. The abdomen was then opened and the following organs were removed in sequence, cleaned of extraneous tissue, blotted, and weighed on individual tares: liver, spleen, testes, or ovaries (from animals over 23 days of age). Kidneys were removed and decapsulated. Both kidneys and testes of each individual were pooled for analysis in 2- and 9-day-old rats. In animals 16 days of age and over, kidney cortex was separated from papilla. No analyses were carried out on ovaries of animals younger than 16 days.

All tissues were weighed and then dried at 100° to constant weight for determination of water content. The tissues were placed in tubes containing 10 ml of distilled water and extracted at 4° for at least 2 weeks. Sodium and potassium contents were then determined using an IL emission spectrophotometer.

Although there are differences between body and organ weights of male and female rats at older ages, no consistent and reproducible differences in electrolyte contents or in water contents were found between tissues of animals of the same age; therefore, data from both sexes are pooled for the remaining tissues except ovary and testis. All data are expressed as means plus or minus standard errors. Regression analysis was carried out using the method of least squares and differences are considered to have statistical significance when $p < 0.05$.

Results. In Fig. 1, water contents are shown as a logarithmic function of age. During the postnatal period, the tissue containing the least amount of water is liver, followed by heart, kidney, and spleen having similar water contents. The sex organs have the highest water content with the water content of the testis exceeding that of the ovary.

The most striking feature with respect to water content is that, in liver, heart, kidney, and spleen, the changes undergo a biphasic pattern which is evident from the semilogarithmic relationship shown in Fig. 1. In these tissues, there is a phase of rapid decline in water content ending at 23 days, followed by a phase of much slower decline during which changes in water content are much less and where absolute values approximate mature values. The testis does not show any significant age-dependent change. The ovary shows a gradual decrease in water without any clear inflection.

Sodium and potassium contents of the tissues are shown in Table I. The ratio of Na/K as a function of age is shown in Fig. 2. Changes in Na/K ratios do not parallel the changes in water content. As might be expected from high extracellular fluid (ECF), tissue sodium content is high relative to po-

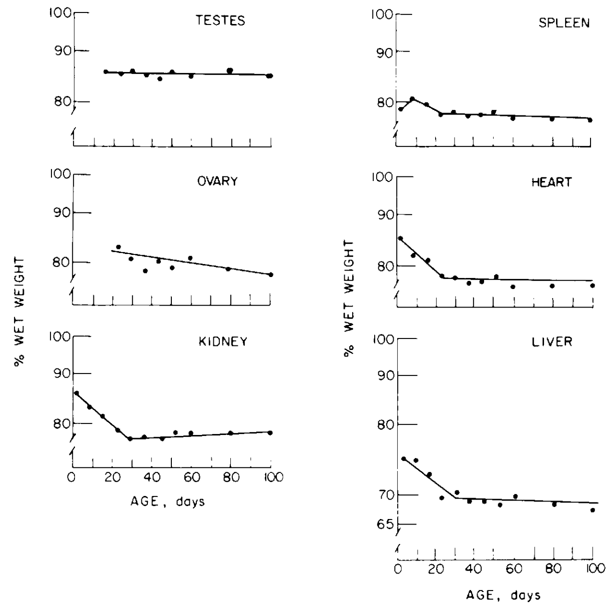

FIG. 1. Water content as a percentage of wet weight for the various tissues studied. Each panel shows data for a single organ.

tassium in the early postnatal period and undergoes a decrease (Table I and Fig. 2). In contrast to water content, however, the Na/K ratio reaches a minimum when the rats are 37 to 44 days old; thereafter, a rise in Na/K ratios occurs for liver, spleen, kidney cortex, and testis, while heart maintains a constant Na/K ratio.

Electrolyte contents of papilla and ovary (Table I) show different patterns. Papillary sodium content is low at 16 days of age. Sodium content is much higher thereafter as might be expected from the observation that the concentrating mechanism assumes mature characteristics during the third week of life in rats (1, 5). An unexpected finding is that ovarian sodium content was found to parallel the papillary pattern over those age ranges where we could measure ovarian electrolytes. In Fig. 3, average ovarian Na is plotted as a function of the average Na in the papilla for each female rat in this study. It is evident that the values of both ovary and papilla increase in parallel. These values have been fitted by a linear least-squares relationship, the equation being $Na_{ov} = 132 + 0.679\ Na_{pap}$. The r value of 0.606 ($p < 0.02$) shows that there is a significant correlation.

In Fig. 4, the sum of Na and K (expressed per kilogram of tissue water) is shown as a function of age for each tissue except ovary and papilla. When examined in this way, a maximum in cation content occurs at 16 days of age for heart, kidney, and spleen. At later times, there is a continuous sharp decrease in the sum of Na and K until about 40 days. A gradual decrease may continue thereafter. In the case of liver, the changes are insignificant.

Discussion. The results of this study demonstrate a dissociation between the decrease in water content and the changes in Na/K ratio for all of the tissues analyzed except for papilla and ovary, similar to that found by others in muscle and brain (5, 6). It is of interest that the reduction in water content occurs at the time of weaning, which is also a "critical time" for the development of urinary-concentrating ability (5, 7) and spontaneous reduction of plasma renin activity (8). On the other hand, the Na/K ratio reaches its minimal value at 35–45 days of age. At this time, the kidney of the rat becomes able to respond to blood volume expansion (9), and baseline excretion of sodium and potassium reach mature levels (10). It would appear that in the postnatal period, one finds a dissociation of development of water and electrolyte regulation. One can also suggest

TABLE I. ELECTROLYTE CONTENTS AS A FUNCTION OF AGE.[a]

Age (days)	Heart		Liver		Ovary		Spleen		Kidney cortex		Papilla		Testis	
	Na	K	Na	K	Na	K	Na	K	Na	K		K	Na	K
2	—	—	38.6 ± 3.2	84.5 ± 6.3	—	—	—	—	85.4 ± 6.7[b]	29.6 ± 7.7[b]	—	—	—	—
9	82.7 ± 15.5	64.3 ± 15.7	23.1 ± 1.3	75.7 ± 1.9	—	—	51.6 ± 12.7	112 ± 6.2	57.8 ± 4.4[b]	73.0 ± 1.9[b]	—	—	—	—
16	71.7 ± 9.8	81.5 ± 2.7	29.0 ± .81	71.6 ± 5.5	177	31.3	121 ± 16.2	114 ± 3.8	114 ± 5.5	76.0 ± 3.2	76 ± 19.7	23.6 ± 11.1	23.3 ± 0.45	11 ± 0.65
23	71.2 ± 3.6	92.7 ± 2.0	20.0 ± .27	76.9 ± 0.9	526	305	56.6 ± 5.0	118 ± 11.6	75.3 ± 3.3	85.9 ± 2.1	426 ± 45.9	217 ± 12.8	105 ± 11.0	109 ± 1.0
30	53.3 ± 2.0	81.3 ± 3.1	18.3 ± 1.1	78.7 ± 2.7	455	76.1	36.0 ± 1.9	111 ± 3.5	57.7 ± 1.6	75.4 ± 1.8	347 ± 14.3	128 ± 35.4	55.8 ± 2.0	95.3 ± 0.24
37	36.6 ± 1.8	81.6 ± 2.0	14.6 ± .33	79.7 ± 1.3	179 ± 30.2	169 ± 33.7	22.3 ± 0.34	122 ± 1.9	41.3 ± .88	72.2 ± 1.8	160 ± 6.5	92.6 ± 5.7	38.8 ± 2.4	85.8 ± 1.6
44	36.1 ± 4.9	79.2 ± 2.3	15.8 ± 2.9	76.9 ± 1.5	304 ± 127	—	24.0 ± 1.7	131 ± 7.7	49.5 ± .75	77.8 ± 2.1	393 ± 48.3	—	39.8 ± 1.6	92.6 ± 1.9
51	39.2 ± 0.75	82.6 ± 4.4	15.0 ± 1.4	71.4 ± 4.5	252	43.2	23.9 ± 1.6	127 ± 5.9	46.4 ± 3.2	70.3 ± 1.5	238 ± 74.5	—	38.8 ± 1.6	88.7 ± 4.8
60	32.8 ± 1.0	75.1 ± 1.0	17.7 ± 1.2	78.9 ± 1.9	156 ± 15.6	74 ± 1.1	24.4 ± 0.41	111 ± 2.3	43.8 ± 1.5	60.5 ± .34	169 ± 6.4	57.6 ± 3.7	35.6 ± 0.88	75 ± 0.83
80	30.3 ± 1.1	75.6 ± 6.1	15.2 ± 1.1	68.4 ± 9.7	301 ± 47.3	162 ± 13.3	19.5 ± 2.2	102 ± 11.6	40.3 ± 2.0	72.7 ± 4.5	177 ± 26.1	76.1 ± 6.2	32.8 ± 1.5	90.1 ± 6.9
100	35.8	74.5	16.6	74.7	363	142	36.6	107	45.6	63.7	284	91.3	46.7	80.9

[a] All data are reported as milliequivalents per kilogram of wet weight. [b] These data represent whole kidney electrolytes.

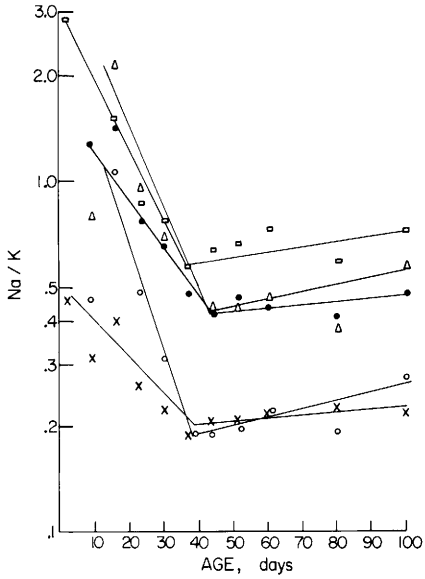

FIG. 2. Ratio of sodium to potassium tissue contents as a function of age. Points (●) represent heart; ○ = spleen; × = liver; △ = testis; and □ = kidney cortex. The same symbols are used in Fig. 4.

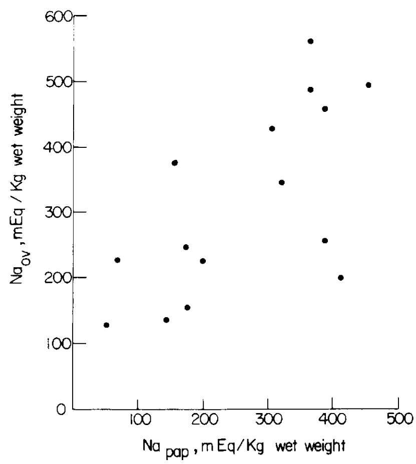

FIG. 3. Relationship between sodium content of ovary (Na_{ov}) and papilla (Na_{pap}). Each point shows mean data from one animal.

that, since the development of renal regulation coincides with internal regulation, the cellular processes and renal homeostatic events are linked.

It is tempting to speculate that the linkage of regulatory development of electrolyte homeostasis is through maturation of transport processes. In support of this hypothesis, one can point to the increase in renal Na-K-ATPase which occurs during the prenatal

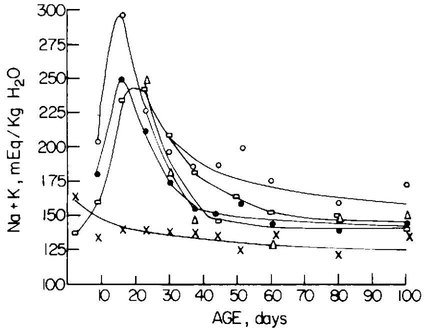

FIG. 4. Sum of sodium and potassium contents expressed as milliequivalents per kilogram of tissue water as a functon of age. Symbols for tissues are the same as in Fig. 2.

period (11). The change in transport capacity, however, is dissociated from the developmental pattern of electrolyte balance and does not account for the fact that the sum of the cations decreases in the period examined (Fig. 4). In muscle and brain, such changes parallel an increase in tissue nitrogen (2, 3). At this point, one can only speculate as to what factors may be involved in reduction of the sum of Na and K. The increase in nitrogen (reflecting an increase in protein) may, however, cause changes in Donnan effects or may possibly reflect a change in the state of tissue electrolytes; i.e., different binding capacity (12).

The most surprising result obtained in these studies is the observation of high ovarian sodium which parallels papillary sodium (Fig. 3). The fact that papillary sodium is high is well known (6) and readily explained on the basis of the countercurrent system of the papilla. No comparable system is known for the ovary. It will be of interest to determine the mechanism which underlies high ovarian sodium and what its functional role may be.

Summary. Electrolyte and water contents of heart, liver, kidney, spleen, ovaries, and testes were analyzed in rats between 2 and 100 days of age. Tissues were dried to constant weight to measure water content. Electrolyte content was determined using emission spectrophotometry. At all times, the liver contained the least amount of water; the kidney, spleen, and heart had an intermediate water content which were approximately equal to each other; the testes and ovaries contained the highest content of water. Water contents of the liver, heart, spleen, and kidney fall from 2 to 23 days of age and then remain constant at adult levels. The water contents of testes and ovaries remain relatively constant throughout the period studied. Tissue Na content of the heart, liver, kidney, spleen, and testes is high relative to K in the early postnatal period and decreases with age, reaching a minimum at 37–44 days of age. The most unexpected result of this study is the finding that the Na content of the ovary parallels that of the kidney papilla during all the periods examined. In both these tissues, Na content is low at 16 days of age and is higher thereafter. These results demonstrate a dissociation between maturation of water and electrolyte balance.

This work was supported by two grants from the National Science Foundation, BMS-72-02344-A02 (to S.S.) and PCM-71-01528 (to A.R.). We also wish to thank Ms. Carolyn Sanborn and Ms. Susan Hathaway for their expert technical assistance.

1. Basso, N., Blaquier, P., De La Riva, I. J., and Taquini, A. C., Acta Physiol. Lat. Amer. **18,** 19 (1968).
2. Vernadakis, A., and Woodbury, D. M., Amer. J. Physiol. **203,** 748 (1962).
3. Vernadakis, A., and Woodbury, D. M., Amer. J. Physiol. **206,** 1365 (1964).
4. Widdowson, E. M., and Dickerson, J. W. T., *in* "Mineral Metabolism: An Advanced Treatise" (C. L. Comar and F. Bronner, eds.), Vol. 2, Part A, p. 17. Academic Press, New York (1964).
5. Trimble, M. E., Amer. J. Physiol. **219,** 1089 (1970).
6. Ullrich, K. J., and Jarausch, K. H., Pflügers Arch. Gesamte Physiol. Menschen Tiere **262,** 537 (1956).
7. Boss, J. M. N., Dlouha, H., Kraus, M., and Krecek, J., J. Physiol. **168,** 196 (1963).
8. Solomon, S., Iaina, A., and Eliahou, H., Physiologist **18,** 399 (1975).
9. Bengele, H. H., and Solomon, S., Amer. J. Physiol. **227,** 364 (1974).
10. Solomon, S., Bengele, H. H., and Smith, W., *in* "Proceedings of the XXVI International Congress of Physiological Sciences." New Delhi, India (1974).
11. Geloso, J. P., and Basset, J. C., Pflügers Arch. 348, 105 (1974).
12. Ling, G. N., "A Physical Theory of the Living State." Blaisdell, New York (1962).

Received June 2, 1976. P.S.E.B.M. 1976, Vol. 153.