Urinary Concentrating Processes in Vertebrates

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Avian and mammalian kidneys can produce a urine hyperosmotic to the blood by means of a renal countercurrent system. Birds are uricotelic; mammals are ureotelic. It is proposed that the inner medulla present in mammalian, but not in avian kidneys serves specifically to accumulate urea in the inner and outer medulla. Among mammalian kidneys the degree to which urea accumulates in the inner medulla is inversely related to the complexity of the vascular bundles (in the outer medulla) and the cortical urea recycling index. A model is proposed for urea recycling via the vascular bundles. The renal pelvis varies in size among mammals. Its relative size is unrelated to the type of vascular bundles, cortical recycling index, or urea accumulation in the inner medulla. Since urine refluxes into the renal pelvis during rising urine flow only, the function of the pelvis could be that of bringing the more dilute urine into contact with the outer medulla and underlying capillaries, thereby aiding in reducing the urea concentration in outer and inner medulla during rising urine flow. The size of the renal pelvis may be related to the volume of the inner medulla. Other factors may also be involved.

This presentation deals with the kidneys of birds and mammals. I shall try to elucidate the intimate relationship between structure and function and suggest how comparative anatomical and physiological studies may lead to new insights into physiological mechanisms.

It is well known that only a few classes of vertebrates are able to produce a urine with an osmolality higher than that of the blood. Only birds, mammals, and probably a few reptiles have this ability. The physiological need for excreting a hyperosmotic urine is a combination of the need for conserving water and excreting excess solutes, and these combined needs confront terrestrial animals only. It is not only the need for conserving water, however, but also the type of nitrogenous waste which is excreted which determines the need for producing a hyperosmotic urine [1,2]. Reptiles and birds excrete uric acid, while mammals excrete urea as the main nitrogenous waste product.

Thus, the majority of reptiles from arid habitats eliminate nitrogenous waste together with K and Na as precipitated urates in a urine isosmotic with the blood. This is a very effective way of concentrating solutes in the urine with a minimal amount of water while the urine remains isosmotic to the blood. This concentration process takes place in the cloaca through the active reabsorption of Na and Cl and passive reabsorption of water [3]. Only when the intake of inorganic anions is high does the reptile need a mechanism for excreting inorganic salts in a solution hyperosmotic to the blood. For this excretion extrarenal salt glands which can efficiently secrete inorganic Na and K salts have developed independently in turtles, lizards, snakes, and birds [4]. Mammals, on the other hand, must use a fundamen-
tally different method for eliminating their organic waste since urea is highly soluble. Consequently, water conservation cannot be achieved unless the kidneys can produce a hyperosmotic urine. The type of kidney needed by mammals to concentrate urea also concentrates electrolytes effectively. Extrarenal salt glands are therefore not necessary in mammals and, in fact, no mammals have extrarenal salt glands.

COMPARISON BETWEEN AVIAN AND MAMMALIAN KIDNEYS

Birds, which like reptiles are uricotelic, have in addition developed a renal concentrating mechanism. Why this mechanism exists is not known, but it may be necessitated by the increased need for water conservation imposed by the need for evaporative cooling during flight. The mechanism serves only to concentrate electrolytes in the urine since the excretion of nitrogenous waste in the form of precipitated urates requires no mechanism for making the urine hyperosmotic. It makes good sense that if an organism excretes uric acid which can precipitate out in the kidney, it is better not to concentrate the urine too much in the renal tubules. Nevertheless, all birds have kidneys with a countercurrent system.

It is interesting that in birds physiological adaptation to the consumption of water of high salinity has been achieved in two different ways: in oceanic birds such as seagulls, terns, pelicans, petrels, and cormorants the kidneys apparently do not concentrate the urine to a high degree and a major portion of the ingested salt is excreted extrarenally via the salt glands. In the birds belonging to the order Passeriformes, which have adapted to salt marshes, extrarenal salt secretion has not developed and the kidneys have developed a higher capacity for concentrating the urine [2]. The reason for this difference is not clear.

In the following I shall discuss the anatomy and physiology of the kidneys of birds and mammals in order to point out some differences associated with the excretion of uric acid versus urea. First I shall deal with birds, where the countercurrent system seems less complicated than in mammals. The bird kidney has retained many of the characteristics of the reptilian kidney from which it evolved [5]. The superficial cortex of the kidney is organized into repeating units in much the same way as in the lizard kidney (see Fig. 1). Each unit has a large efferent vein forming the center of the unit. Arranged in a radiating fashion around the central veins are nephrons that do not possess loops of Henle or intermediate segments. These nephrons empty into the collecting ducts in the periphery of the unit. The collecting ducts are oriented at right angles to the nephrons. This arrangement of the tubules is typical of almost all reptilian kidneys and these nephrons, called reptilian-type nephrons, are probably associated with uric acid secretion. A kidney consisting of this type of nephron only is not able to produce a hyperosmotic urine.

It is the cone that is characteristic of bird kidneys. The cones are surrounded by and isolated from the cortical tissue by connective tissue (see Fig. 2). Often several cones become contiguous, forming a group of cones which are then enclosed in a common sheet of connective tissue [7]. The structures in the cones consist of the collecting ducts which join to form larger collecting ducts and finally join the ureteral branch directly. The collecting ducts are thus extensions of the ureter which exhibits powerful peristaltic contractions [8].

The nephrons in the cones are mammalian-type nephrons. These nephrons resemble the short-loop nephrons of mammalian kidneys in that only the descending limb of the loop is thin. They turn in the thick limb and all of the ascending limbs are thick. Not all loops are as long as the cone (Fig. 1), just as, in the mammalian kidney, some bend near the base of the cone. Within the cones (Figs. 2 and 3), arranged in a
FIG. 1. *One lobule from a bird kidney (desert quail)*. Reprinted from Braun and Dantzer [6] with the permission of the authors. For further description, see text.

FIG. 2. *Medullary cones from a bird kidney*. Semidiagrammatic representation from *Carpodacus mexicanus*. Reprinted from Poulson [7] with the permission of the author. (A) A parasagittal section through one kidney showing medullary portions on both sides of the plane of sectioning. (B) Transverse section through the anterior-most kidney lobe. (C) An enlarged view of the medullary portion of the kidney as shown in B. (D1, D2, D3) cross sections of an individual medullary lobule progressing from near the cortex toward its connection with a ureteral branch. Designations are as follows: a, cortex; b, medulla or cone; b1, thick segments of Henle's loops; b2, layers of Henle's loops; b3, ring of collecting tubules around capillaries and thin Henle's loop segments; c, ureter; d, connective tissue sheath around medullary cone; e, thin Henle's loop segment; f, capillary; g, collecting tubule; and h, ureteral branches. Copyright 1965, by the American Association for the Advancement of Science.
parallel fashion are the thick ascending limbs which are the most superficial. Inside the ring of ascending limbs, the collecting ducts are often arranged in a circle. Inside these are the thin limbs of Henle and the vasa recta. The arrangement resembles that of the outer medulla of some mammalian kidneys. But then again, the medullary cone of the bird kidney corresponds to the outer medulla of the mammalian kidney because there are no ascending thin limbs of the loop of Henle.

In birds the degree to which kidneys can concentrate the urine appears to be determined by two anatomical characteristics; namely, the relative number of medullary cones, and the length of the medullary cones. In earlier studies Poulson [6] found a correlation between the relative number of medullary cones and the concentrating ability, but no relationship between the average length of Henle's loops and concentrating ability. This is not surprising since it is the longest loops only and not the average length of the loops which determines the length of the medullary cones. Indeed, in a recent study of Johnson and Skadhauge [10] the length of the medullary cones in a number of Australian birds was found to be directly correlated with the renal concentrating ability (refer to Table 1). In mammals, also, the length of the inner medulla shows a good correlation to the concentrating ability [11].

It is NaCl, mostly, and not nitrogenous waste products that are concentrated in the tissue of the medullary cone. Skadhauge and 1 [12] analyzed the renal cones of the kidneys of domestic fowl and found that Na and Cl are concentrated in the cones and that the concentration increases toward the tip of the cone. There was a significantly higher concentration of Na and Cl in the cone compared to the cortex. K increased toward the tip in dehydrated birds but not in salt-loaded birds. Urea increased only

### TABLE 1
Relative Thickness of the Renal Medulla and Associated U/P Ratios

| Species            | Relative Length of Medullary Cones | Mean U/P Ratios |
|--------------------|------------------------------------|-----------------|
| Emu                | 1.10                               | 1.4             |
| Senegal Dove       | 2.62                               | 1.7             |
| Kookaburra         | 3.00                               | 2.7             |
| Singing Honeyeater | 3.56                               | 2.4             |
| Zebra Finch        | 4.71                               | 2.8             |

From Johnson and Skadhauge [10].
slightly in the cone and its low concentration (1 to 2 mM) contributed less than 0.5 percent to the osmolality of the cone tissue. The increase in osmolality of the cone could essentially be accounted for by the increase in Na and Cl ions in the salt-loaded bird ([12] and Fig. 4).

The countercurrent system in the bird kidney thus appears to function primarily by concentrating sodium chloride. Microcryoscopy of frozen sections of the medullary cone from bird kidneys [13] showed that the osmolality is highest in the thick

![Diagram](image-url)

**FIG. 4.** Comparison between solute gradients in mammalian and bird kidneys (adapted from [12] and [16]). The kidney of the mountain beaver shown on the left does not have an inner medulla. The medulla labelled OZ1, OZ2 and OZ3, has short looped nephrons only, as in the bird kidney. The cone of the bird kidney is labelled M1, M2, and M3. In both mountain beaver and turkey urea contributes little to the solute concentration of the medulla. 30 mM in mountain beaver medulla, 2 mM in turkey kidney.

The urea tissue-to-plasma ratio was 2.5 in mountain beaver (on high protein diet, HP) and 2.14 in the cone of the turkey. Na concentration rises to a maximum of 150 mM in the medullary tissue of the mountain beaver kidney and to 135 mM in the cone of the turkey.
ascending limbs and lowest in the capillaries. Countercurrent exchange between ascending and descending vasa recta and descending thin limbs of the loops of Henle can help maintain the Na gradient in the cone. The exact role of each of the tubular and vascular structures in the cone is difficult to ascertain without further experimentation. At this time we do not know anything about the relative permeabilities to water and ions of these structures. Very little work has been done on the cone of the bird kidneys due to the inaccessibility of this tissue. The cones are surrounded on all sides by cortical tissue from other renal units.

If we now compare the structure and function of the bird kidney (Fig. 1) with that of the mammalian kidney (Fig. 5) we see some important differences. First, the population of nephrons differ. In the bird kidney there are the reptilian-type nephrons without the loop of Henle and the mammalian-type nephrons with the loop of Henle. In the mammalian kidney all nephrons have loops of Henle. Second, mammalian-type nephrons in the bird kidney correspond to the short-loop nephrons in the mammalian kidney. This type of nephron has a thin descending limb and a thick ascending limb of the loop of Henle. In most mammalian kidneys some nephrons are short-looped, while other nephrons are long-looped and have thin descending and ascending limbs of the loop of Henle (see Fig. 5). Mammalian kidneys in which long-looped nephrons are present have an inner medulla. There is no inner medulla in a bird kidney. Third, in the bird kidney the collecting ducts join a branch of the ureter directly, while in the mammalian kidney the collecting ducts end on the tip of the papilla or crest. Fourth, in the bird kidney the medullary cone is surrounded by a sheet of connective tissue which separates the medullary cone from the surrounding cortical tissue. In the mammalian kidney, the inner medulla is surrounded by the urinary space of the renal pelvis (Fig. 6). Finally, in the bird

![Diagram of a section of a human kidney including one papilla.](image)

**FIG. 5. Schematic drawing of a section of a human kidney including one papilla.** From v. Möllendorph [5]. Reprinted with permission of Springer-Verlag. In the human kidney the shortest loops of Henle turn in the cortex (Rinde). The typical short loop nephrons of most mammals turn in the outer medulla (Aussen-Zone) into the thick ascending limb (Breiter Teil der Schleifen). In the inner medulla (Innen-Zone) the loops of Henle have thin ascending as well as descending limbs (Dünner Teil der Schleifen). The collecting ducts (Sammelrohr) open on the tip of the papilla. The vascular bundles are biggest in the outer medulla (shown in the cross sections), and are more dispersed in the inner medulla.
URINARY CONCENTRATING PROCESSES IN VERTEBRATES

FIG. 6. Renal pelvis from human kidney. Reprinted from Narath [14] with the permission of the publisher. The renal medulla is surrounded by the urinary space of the pelvis (Pel., called the calyx in multipapillate kidneys).

Kidney sodium and chloride ions (but not urea) accumulate in the medullary cone, raising the osmolality of the tissue. In the mammalian kidney, urea, sodium, and chloride accumulate in the outer as well as the inner medulla (Fig. 7) [11,15].

We can assume that these differences are primarily a consequence of the difference in metabolic end product of the nitrogen metabolism of birds and mammals. A kidney which does not concentrate urea apparently does not need an inner medulla with long, thin loops of Henle, nor does it need a renal pelvis which can bring the urine into contact with the outer and inner medulla. The medullary cone of the bird kidney, on the other hand, has some structural similarities with the outer medulla of the mammalian kidney. In many mammalian kidneys the thin descending limbs of the short loops of Henle are incorporated into the capillary bundles. This type of capillary bundle corresponds, at least superficially, to the central core of the cone of the bird kidney where thin limbs of the loop of Henle intermingle with ascending and descending capillaries. The interbundle area of the mammalian outer medulla contains in most species collecting ducts and thick ascending loops of Henle together with thin descending limbs of the long loops of Henle. This corresponds to the ring of collecting ducts and thick ascending limbs of the loop of Henle surrounding the capillaries in the bird kidney. In mammalian kidneys devoid of an inner medulla (beaver, Castor, and mountain beaver, Aplodontia) Na and Cl but little urea accumulate in the outer medulla [17].

COMPARISON BETWEEN MAMMALIAN KIDNEYS

In the following I shall focus the attention on two anatomical features of the mammalian kidney which are functionally poorly understood, namely the vascular bundles and the renal pelvis. I shall try to elucidate their function through a physiological and anatomical comparison between the kidneys of four different species of mammals. The mammals are dog, rat, gerbil (Meriones), and sand rat (Psammomys).
FIG. 7. Solute concentrations in renal tissue in dog, gerbil (Meriones), and sand rat (Psammomys). Dotted lines and open circles represent animals on normal or high protein diets. Solid lines and closed circles represent low protein fed animals. Data for dog from Schmidt-Nielsen and Robinson [15], data for gerbil and sand rat from Trimble [16] and Trimble and Schmidt-Nielsen (in preparation).

Cortex samples indicated by C, outer medulla by OZ, inner medulla by IZ, and urine by U. The concentrations are shown on the ordinate on a logarithmic scale.
Physiological Findings

In earlier studies my collaborators and I found that the degree to which urea accumulates in the inner medulla in these species is not the same [15,16,18]. From Fig. 7 it can be seen that in the dog on a normal protein diet the average urea concentration in the inner medulla increases steadily from outer through inner medulla. Similar observations were made in the rat [19]. In gerbil and sand rat, on the other hand, the tissue urea concentration levels off in the inner medulla and decreases slightly toward the tip. When the animals are maintained on a low protein diet, the pattern of urea distribution in the inner medulla is rather similar in rat [19], dog, gerbil, and sand rat (Fig. 7). When one compares the maximum tissue urea concentration with the urine urea concentration (Fig. 8) it can be seen that in the dog the urea concentration in the inner medulla increases almost in direct proportion to the increase in urine urea concentration, the maximum urea concentration in the papilla being 1,400 mM.

In the rat a similar relationship is seen, but the urea concentration in the inner medullary tissue does not reach as high a value as in the dog. The urea concentration in the tissue begins to level off before 1,000 mM, and as the urea concentration in the urine continues to increase, it increasingly exceeds that of the papillary tissue. In the sand rat and in the gerbil the tissue urea concentration rises with the urine urea concentration up to 500 mM, but then begins to level off and does not exceed 700–800 mM, even when the urine urea concentration reaches 2,000 mM.

The fact that in some mammals the inner medullary urea concentration rises with increasing urea concentration in the urine and not in others appears to be closely
related to the fact that increased urea excretion enhances renal concentrating ability in some animals and not in others [18]. Gamble et al. [20] found that in rats in which the ratio of urea to NaCl in the urine was varied over a wide range the highest concentrating ability was found when urea constituted about 65 percent of the total solute excretion. This specific effect of urea upon the renal concentrating ability has since been demonstrated in several other mammalian species, including the dog [18,21,22]. It is, however, not universal for all mammals (Rabinowitz, personal communication). Indeed, in gerbil and sand rat a relative increase in urinary urea excretion does not enhance the concentrating ability [16,18].

Finally, another physiological difference in handling of urea is evident among mammalian species, namely, the so-called recycling index [23]. When micropuncture samples are taken from the early distal tubules on the surface of the kidney the fraction of filtered urea present in the tubular fluid can be determined (if the animal is being infused with a glomerular marker such as inulin). This index exceeds unity in most animals, indicating that urea has been added to the tubular fluid. From Table 3 it can be seen that the highest index is found in sand rat in which more than four times the amount of urea filtered in the glomeruli is present in the early distal convolutions.

**Anatomical Findings**

Kriz and his colleagues have studied the vascular bundles in a number of species including rat [24], gerbil [25], and sand rat [26]. In the dog [27] the vascular bundles in the outer medulla consist of ascending and descending vasa recta, only. All the nephrons in the dog kidney are long-looped nephrons and the descending limbs of these nephrons are located in the interbundle area among the collecting ducts and ascending thick limbs of the loops of Henle. In the rat the situation is different. The vascular bundles again consist exclusively of ascending and descending vasa recta, but the thin limbs of the short loops of Henle are located in a circular fashion surrounding the vascular bundles (Fig. 9). As in the dog, the thin limbs of the long loops of Henle are located in the interbundle area. The gerbil and sand rat both have complex vascular bundles (Fig. 10). This pattern is most pronounced in the sand rat. The thin limbs within the bundles have a smaller diameter and a much thinner epithelium than those of the long-looped nephrons [26] (situated in the interbundle area). Kaissling et al. [26] wrote about the sand rat kidney: "The bundles consist of arterial vasa recta (8–14%), venous vasa recta (39–47%) and thin descending limbs of the loop of Henle (44–51%), which are derived from short loops only. In a typical

![FIG. 9. Vascular bundle in the outer medulla of the rat kidney.](image) Reprinted from Kriz [25] with the permission of the author. The ring of descending limbs (DL) surrounding the ascending (AVR) and descending (VVR) vasa recta in the capillary bundles.
giant vascular bundle run 70–150 arterial vasa recta, 300–600 venous vasa recta, 350–700 thin limbs." Thus, these vascular bundles favor countercurrent exchange between ascending vasa recta and descending thin limbs of the short loops of Henle. As in the dog kidney, the thin limbs of the long loops of Henle run in the interbundle area where the collecting ducts and the ascending thick limbs of the loops of Henle are located.

The renal pelvis, which we have described in detail for the hamster [28] is very different in the four species discussed here. For simplicity, the casts of the renal pelvis only are shown for the four species (Figs. 11 and 12). It is readily apparent that the pelvis of the dog and of the sand rat are by far the most elaborate. Pelvises of this type indicate that a large area of the outer medulla of the kidney is exposed to the pelvic urine. The pelvises of the gerbil and the rat are more moderate. Measurements of pelvic surface area of the rat, gerbil, and sand rat show that the pelvis is much

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FIG. 10. *Vascular bundle in the outer medulla of the gerbil kidney.* Reprinted from Kriz [25] with the permission of the author. The descending limbs of the loop of Henle (DL) are incorporated within the vascular bundles along with ascending (AVR) and descending (VVR) vasa recta. The collecting ducts (CD) and ascending limbs of the loops of Henle (AL) are found in the interbundle area.

FIG. 11. *Neoprene casts of the pelvis of the dog kidney and the rat kidney.* Reprinted from Pfeiffer [29] with the permission of the author. (1) cast of a kidney of a dog highly developed secondary pouches (SP) and fornices (F) are present; (2) cast of a rat pelvis showing only slight secondary pouches and not very elaborate fornices.
FIG. 12. Neoprene casts of the renal pelvises of the sand rat and gerbil. Reprinted from Trimble[16] with permission of the author. I. Sand rat pelvis (1a) seen from the side, (1b) seen from the top of the pelvis. Secondary pouches are highly developed. The fornices are best seen from the top view of the same cast (F). They are very elaborate and extend almost to the midline of the kidney. II. Casts of the kidney of the gerbil (1a) side view; (1b) view from the top. Secondary pouches are missing; fornices (F) are not as elaborate as in the cast from the sand rat.

larger in the sand rat than in the rat (Table 2). In the sand rat the surface area of the pelvis is almost as large as the outer surface area of the entire kidney, while in the rat it is only 25 percent of the kidney surface area. Similarly, the relative surface area of the outer medulla facing the renal pelvis is four times as large in the sand rat as in the rat. Unfortunately, we do not have such measurements for the dog kidney. But

|                          | Rat  | Gerbil | Sand Rat |
|--------------------------|------|--------|----------|
| Pelvic Surface Areas in Percent of Kidney Surface |      |        |          |
| Total Pelvis             | 25.0 | 48.7   | 97.2     |
| Outer Medulla            | 13.8 | 25.5   | 52.0     |
| Ratio of surface area to volume |      |        |          |
| Outer medulla mm² inner medulla mm³ | 3.26 | 3.10   | 3.51     |
judging from the shape of the cast of the renal pelvis from the dog, it is probable that
the relative surface area of the dog pelvis is similar to that of the sand rat.

There are other interesting features concerning the pelvis of the sand rat. Kaissling
et al. [26] have shown (Fig. 13) that the renal pelvis in the sand rat almost surrounds
and isolates the vascular bundles. In our studies of the hamster kidney we found the
capillaries to be directly under the pelvic epithelium [30], but we did not find the type
of pelvic structures where the vascular bundles were particularly exposed to the
pelvis.

HYPOTHESIS

We can now compile the data discussed above into a single table (Table 3). The
trend seen among these four species of mammals is that the urea concentration at the
papillary tip appears to be inversely related to the complexity of the vascular bundles.
Furthermore, urea does not enhance the urine osmolality in the species which have
complex vascular bundles. And, finally, the degree to which urea is recycled within
the outer medulla and cortex is directly proportional to the complexity of the vascular
bundles.

The following model for the vascular recirculation could explain these correlations
(see Fig. 14): in the sand rat urea added to the interstitial fluid from the collecting
ducts (or pelvic urine at the papilla) would enter the ascending vasa recta. In the
complex vascular bundles in the outer medulla a major part of this solute would be
transferred to the descending limbs of the short loops while a smaller part would be
transferred to the descending vasa recta. Of the fraction of urea returning to the
nephrons, not all would return to the inner medulla due to loss to the capillaries in
the cortex. In fact, a smaller fraction of filtered urea is excreted by sand rat than by
dog [11]. In the dog kidney, on the other hand, urea entering the ascending vasa recta
would be returned more completely to the inner medulla since the vascular bundles
consist of ascending and descending vasa recta only. Thus, urea added to the inner
medulla would be recycled more efficiently by the vascular system and result in a
higher urea concentration in the inner medulla. In this discussion the recycling via the
long-looped nephrons has not been taken into account, since the difference under
discussion concerns the vascular bundles. The model proposed from the present data
differs from that proposed by Valtin [23] in that the complex vascular bundles further

FIG. 13. Section through the
pelvis and outer medulla of the sand
rat kidney. Reprinted from Kaiss-
ling et al. [26] with the permission
of the author. The vascular bundles
(VB) are surrounded on all sides by
the extensions of the pelvis. These
extensions correspond to the elabor-
ate folds of the pelvis seen on the
cast in Fig. 12.
the removal of urea from the inner medulla rather than help to increase the urea concentration in the inner medulla.

While the complexity of the vascular bundles appears to be closely related to the physiological handling of urea in the four species examined, the complexity of the renal pelvis appears to be totally unrelated, at least as far as the functions presented in Table 3 are concerned. This was surprising since the comparison between bird and mammalian kidneys indicated that the development of the renal pelvis is associated with ureotelism in mammals. What, then, is the physiological role of the renal pelvis? We have studied the function of the renal pelvis through visual observations of the urine through the intact pelvic wall in rats and hamsters (Schmidt-Nielsen et al., in preparation). The urine was made green through a constant infusion of lissamine green into the jugular vein. The green urine could clearly be seen through the pelvis and in the collecting ducts. Observations show that the urine, after it leaves the collecting ducts at the tip of the papilla, sometimes refluxes deep into all of the recesses of the renal pelvis, and thus comes into intimate contact with the outer and inner medullary surface areas of the kidney. At other times the urine refluxes only to the tip of the papilla and at times the urine moves straight down through the ureter. The investigation showed that deep refluxes occur regularly during rising urine flow, i.e., when urine osmolality and urea concentration is falling. Under these conditions urea can move from the inner medullary tissue into the urine. Shallow refluxes bathing only the tip of the papilla occur during rapidly falling urine flow, when urine
concentrations are increasing. During steady-state urine flow, the urine flows from the collecting ducts directly down through the ureter.

These findings suggest that deep refluxing serves to lower the medullary tissue urea concentration during rising urine flow. This, of course, is advantageous to the animal since the higher urine flow rate requires a lower solute concentration in the renal medulla (refer to Table 4). Conversely, shallow refluxes occurring during falling urine flow may serve to bathe the papilla with a urine which now has a higher urea concentration than the papillary tissue, thereby increasing the urea concentrations in the papillary tissue.

While these findings suggest a clear function of the renal pelvis in the ureotelic mammals, they still do not explain the difference in the development of the mammalian renal pelvises. Why do some mammals have much larger renal pelvises than others? The answer may lie in the surface-to-volume ratio of the renal medulla. While the relative pelvic surface area varies greatly among species, the ratio between this surface area and the volume of the renal medulla is rather constant (refer to

| Pelvis  | Complex Vascular Bundles | Urea Conc. at Pap. tip (mM) | Does urea enhance urine osm? | Urea recycling TF/P urea over dist. tubule |
|---------|--------------------------|-----------------------------|------------------------------|------------------------------------------|
| Dog     | +++                      | 0                           | 1,000                        | Yes                                      | —                                        |
| Rat     | ++                       | +                           | 850                          | Yes                                      | 1.1                                      |
| Gerbil  | ++                       | ++                          | 500                          | No                                       | 1.7                                      |
| Sand Rat| ++++                     | +++                         | 400                          | No                                       | 4.17                                     |

The relative size of the pelvis has been indicated by crosses. Also, the complexity of vascular bundles is indicated similarly. The values are copies from Valtin [23]. No thin limbs associated with the vascular bundles is indicated by a zero, and the rat, where the thin limbs surround the vascular bundles is given by one cross and in the gerbil and sand rat where the thin limbs of the loop of Henle are included in the vascular bundles are given two and three crosses, respectively. In the next column the maximum concentrations of urea measured at the tip of the papilla are given. This value is lower than shown in Fig. 8 because in gerbil and sand rat the urea concentration is lower at the tip of the papilla than slightly higher up (Fig. 7). The next column indicates whether or not urea enhances the urinary concentrating ability. The last column shows the cortical urea recycling index as shown by Valtin [23]. Data for the dog are not available, but in the rabbit, which has vascular bundles of the same type as the dog, the value is 0.71 [23].

TABLE 4
Concentrations and Amounts of Urea, Sodium, and Water in Inner Medullary Tissue of a Dog During Diuresis and Antidiuresis

| Urea | Na | H2O |
|------|----|-----|
| Concentrations |
| mM | mM | % |
| Diuresis | 35 | 140 | 89 |
| Antidiuresis | 950 | 350 | 79 |
| Amounts per mg Solute-Free Dry Tissue |
| mmoles | mmoles | ml |
| Diuresis | .31 | 1.26 | 8.98 |
| Antidiuresis | 4.52 | 1.66 | 4.78 |
| Difference | 4.21 | 0.40 | -4.20 |
Table 2). Obviously, this means that when an animal has a large volume of inner medulla and therefore a larger accumulation of urea, it takes a larger surface area of the outer medulla to remove a significant fraction of this urea during rising urine flow. Conversely, when the mammal possesses a small volume of inner medulla, the amount of urea which accumulates during antidiuresis is relatively small, and therefore requires a smaller pelvic surface area to be removed.

Because the study of the function of renal pelvis is still in its infancy and thorough comparative anatomical data of pelvic anatomy are missing at this time, the above suggestions are tentative, at best.

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