Heliyon 6 (2020) e03139

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Anatomical features in the kidney involved in water conservation through urine concentration in dromedaries (*Camelus dromedarius*)

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ARTICLE INFO

Keywords:
Kidney
Renal pelvis
Medullary pyramids
Camel
Urine concentration
Water conservation
Urea recycling
Alkaline phosphatase
Renal crest
Pelvic recesses
Biological sciences
Animal physiology
Veterinary medicine
Physiology
Anatomy

ABSTRACT

The aim of this study was to report some of the morphological characteristics of the kidney involved in urine concentration and hence water conservation in the dromedaries. A total of 20 fresh kidneys of 10 apparently healthy camels were used in this study. The architecture of the renal pelvis was revealed by dissection and polyvinyl chloride corrosion casts. Samples were also processed for histology and for enzyme histochemistry. The camel kidney is bean shaped, smooth, multilobar, unipapillary, in which the fusion of renal papillae is complete forming a common renal papilla or crest, which channel urine into a central renal pelvis. It is more or less similar to equine, caprine, ovine and canine kidney. Under certain anatomical requisites the renal pelvis is known to play a role in urine concentration through recycling of urea to increase the medullary osmotic concentration which favors the counter-current mechanism. One of these requisites is an elaborate renal pelvis which is closely associated with the renal medulla. The renal pelvis of the camel has a main crescentic cavity following the long axis and curvature of the kidney. A thick extensive renal crest projects into the cavity of the pelvis. The thick renal crest contains large numbers of long loops of Henle and vasa recta which are important for urine concentration. The renal crest is formed by convergence of the medullary pyramids before it projects into the cavity of the renal pelvis. The crescentic main cavity of the pelvis forms 20–24 three dimensional radiating collateral recesses which contain the medullary pyramids. This close association of the renal pelvis and medulla provide a large surface area for the recycling of urea and hence urine concentration. This large pelvic-medullary interface is lined by simple low cuboidal epithelium which enhances the recycling of urea and water from the pelvic urine into the medulla and directly contributes to urine concentration. The rest of the wall of the renal pelvis and its recesses facing away from the renal crest and medullary pyramids is lined by impermeable transitional epithelium. Another feature is the intense activity of alkaline phosphatase demonstrated in the proximal convoluted tubules which indicates increased membrane transport. It is concluded that the kidney in dromedaries has the anatomical and histochemical requisites for the production of concentrated urine. These requisites enable the kidney to adequately contribute to the ability of the camel to conserve water and withstand the aridity of its habitat.

1. Introduction

It is well established that, only mammals and birds can produce urine with total osmotic concentration more than that of blood plasma [1]. The role of the mammalian kidneys in water balance cannot be overemphasized. The ability of the kidney to concentrate urine received considerable attention and has been the subject of study for decades. This important issue has recently been reviewed [2].

The production of highly concentrated urine is an important factor in water conservation. In order to produce concentrated urine, the kidney must possess certain anatomical features for an effective counter-current system of urine concentration. The medullary architecture and its association with the renal pelvis and transport properties of the nephrons suggest that the anatomic relationships of these structures may contribute to urine concentration [2]. In various mammals the features of renal anatomy vary according to the aridity of the habitat [3]. The camel is known to conserve water through physiological processes including the production of highly concentrated urine [1, 4]. Recent experimental evidence indicated that the camel is able to conserve water during dehydration reduction in kidney solute loads because reduced plasma loads and tubular loads resulted in trapping of constituents in the plasma to hold more water [5]. The structure of the mammalian renal medulla

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https://doi.org/10.1016/j.heliyon.2019.e03139
Received 1 November 2019; Received in revised form 13 December 2019; Accepted 27 December 2019

and the length of the loop of Henle are the main requisites for urine concentrating capacity of the kidney [4, 6, 7, 8, 9]. The division of the medulla into inner and outer zones is a remarkable feature in relating kidney structure to the ability of an animal to form a highly concentrated urine. The ratio between long and short loops varies among species. Humans and most rodents have a larger number of short-looped than long-looped nephrons [10]. The relative medullary thickness is the ratio of the mean thickress of the medulla to the cube root of the kidney volume [3]. It is an index of the length of the loop of Henle. High values of relative medullary thickness (8.5) were found in the kangaroo rat (*Dipodomys),* which produces highly concentrated urine [4], and in the dromedary camel (7.89) as reported in our previous investigation [11]. Furthermore, the architecture of the renal pelvis and its close association with the renal medullary tissue has recently been implicated in the production of concentrated urine. Urea could be recycled from the pelvic urine in species in which the renal pelvis forms folds which facilitate recycling of urea to build up osmotic concentration in the medulla [12, 13, 14]. Although the morphology of the kidneys of camels has been the subject of some studies [15, 16, 17], no precise description of the structure of the renal pelvis and its anatomical and functional relationship to the medulla in the dromedary camel is found in the literature. The study of the normal architecture of the mammalian renal pelvis may have clinical significance. It has recently been found that renal pelvic dilatation in dogs and cats can be detected sonographically under normal renal function, and that it increases with renal insufficiency, pyelonephritis, or outflow obstruction [18]. The anatomy of the renal pelvic space has been described in some detail in the rabbit [19], in the sand rat [20] and in the hamster [21]. In our previous study [11], morphometric parameters of the kidney of the camel involved in urine concentration were outlined.

The major function of the enzyme alkaline phosphatase is transporting across cell membranes [22]. The presence of this enzyme has not been investigated in the kidney of the camel. However, it has been demonstrated in the kidneys of man, monkey, and rodents [23, 24].

This paper describes the architecture and histology of the renal pelvis and its relationship to the renal medulla in the kidney of the camel together with histochemical localization of alkaline phosphatase. These findings are correlated with the known ability of the kidney of the camel to concentrate urine and contribute to water conservation. The terminology used in this article follows the Illustrated Veterinary Anatomical Nomenclature [25].

2. Materials and methods

A total of twenty fresh kidneys in ten apparently healthy (normal) camels were collected from the camel slaughter house where the animals were slaughtered under official license and supervision for meat production. Kidneys with abnormal shapes, hemorrhage or gross pathological signs were excluded. Two methods were adopted to reveal the architecture of the renal pelvis. In the first method the fresh kidneys were injected with 10% vinylite (polyvinyl chloride) in acetone through the cannulated ureter. After injection the cut end of the ureter was ligated and the injected specimens were then left for 2–3 h for the vinylite to set. This was confirmed by examining the ligated end of the ureter. The injected kidneys were then completely submerged in concentrated hydrochloric acid for 24–48 h for corrosion and the resulting casts were washed with tap water. In some specimens the renal artery was also injected with vinylite along with the renal pelvis to reveal the distribution of the branches in relation to the architecture of the renal pelvis. In the second method adopted to study the renal pelvis, the kidneys were fixed by perfusion with 5% formalin through the renal artery. The fixed kidneys were then dissected by removal of the capsule and careful excision of the renal parenchyma until the intact pelvis was obtained. Samples for histology were fixed in 10% formalin and paraffin sections were cut and stained with hematoxylin and eosin.

To investigate the presence of the enzyme alkaline phosphatase in the kidney of the camel both paraffin and cryostat sections were used and the standard histochemical methods of Gomori calcium and the azo-dye coupling methods were applied [26].

3. Results and discussion

Earlier studies on the structure and function of the mammalian kidney have indicated that the production of concentrated urine and hence water conservation depend on three main features. These features are the relative medullay thickness [6], the architecture of the *renal pelvis* [12] and the cortical tubules [11, 27].

Unlike the bovine and porcine kidneys [28], in the present study the dromedarian kidney has no minor and major calyces and individual pyramids do not project into minor or major calyces. Instead, the medullary pyramids converge from the corticomedullary junction to form a thick extensive renal crest *(papilla renalis communis*) which projects into the main cavity of the renal pelvis (Figures. 1 and 2). Such medullary architecture is known as a multilobar, unipapillary kidney, in this respect the camel kidney is similar to the equine, caprine, ovine and canine kidney [28] However, the structure of the renal pelvis of the camel is very elaborate due to the formation of three dimensional extensions emanating from the main cavity (body) of the pelvis.

The relative medullary thickness is an index for both length of the loops of Henle and vasa recta, and a predictor of maximum urine concentrating ability [29]. We calculated this ratio in a previous study [11] and found a value of about 7.89 for the kidneys of the camels. It has been established that mammals living in arid areas had higher values of relative medullary thickness than those of similar-sized mammals from habitats containing a moderate amount of moisture [2]. The thick extensive renal crest is indicative of the presence of a large number of nephrons with long loops which is a requisite for the production of concentrated urine [30]. The main cavity of the pelvis is crescentic in shape with its long axis following the long axis and curvature of the kidney (Figure 1). The smooth medial wall of the main cavity is in contact with the adipose connective tissue of the renal sinus which houses the ureter as it arises from the center of the medial wall of the cavity (Figures. 1 and 2). In longitudinal sections of the kidney the average length of the main cavity of renal pelvis is 8 cm before it curves near the cranial and caudal poles of the kidney (*extremitas cranialis* and *extremitas caudalis*) to enclose the fatty tissue of the renal sinus (Figure 1). The cavity is about 2–3 cm wide. In all anatomical directions within the kidney, except the direction of the renal sinus, the crescentic main cavity of the renal pelvis forms a total of 24 three dimensional radiating fornices (*recesses*

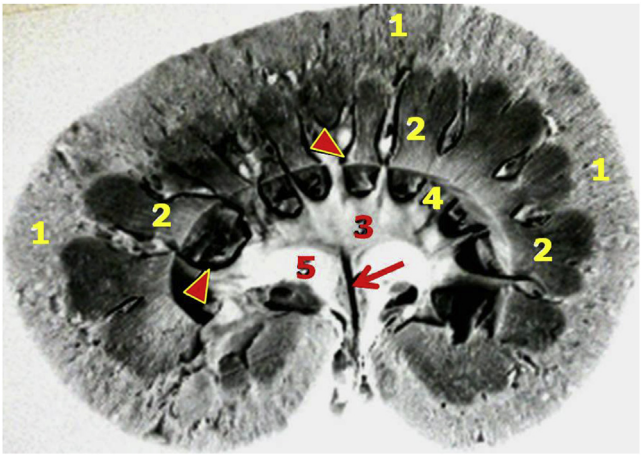

Figure 1. Longitudinal section of the kidney of the camel. The kidney was fixed by perfusion through the renal artery with 5% formalin. The renal crest was excised to expose the underlying part of the renal pelvis. 1, cortex; 2, renal pyramids converging to form the excised renal crest; 3, main cavity of renal pelvis; 4, walls of collateral recesses; arrowheads, collateral recesses; 5, normal fat padding around the ureter(arrow) within the renal sinus(See also Figure 3).

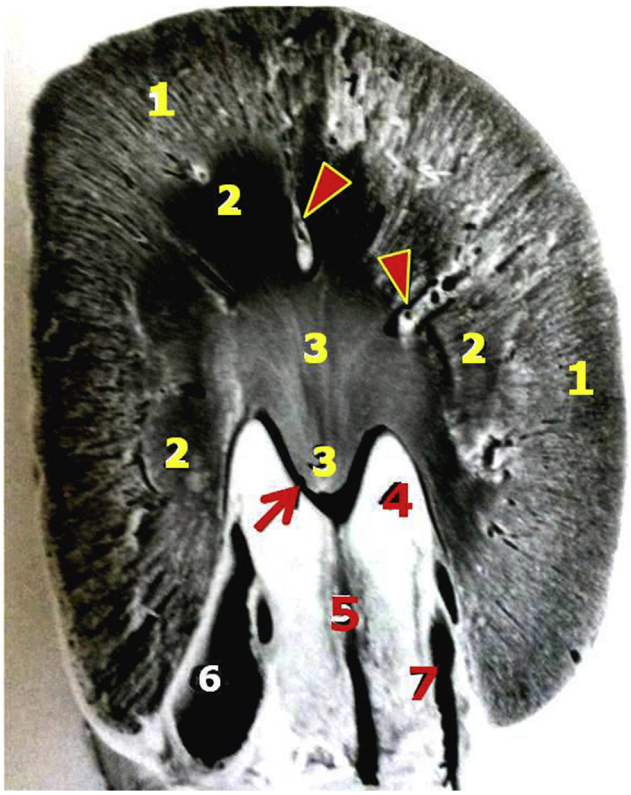

Figure 2. Transverse section of the kidney of the camel. The kidney was fixed by perfusion through the renal artery with 5% formalin. 1, cortex; 2, renal pyramids converging to form the crista renalis 3, renal crest projecting into the main cavity of renal pelvis (arrow); 4, fat padding in the renal sinus; 5, ureter; 6, stump of renal vein; 7, branch of the renal artery. Notice the walls of collateral recesses (arrowheads), separating the renal pyramids before they converge to form the renal crest.

collaterales) containing the converging medullary pyramids (Figures. 1, 2, and 3). The 24 fornices (recesses) are equally distributed between the dorsal and ventral halves of the renal pelvis (Figures 3 and 4). The interlobar branches of the renal artery and vein pass between the fornices of the renal pelvis (Figure 5).

The highest osmotic gradient is generated in the inner medulla. In rats producing maximally concentrated urine, the interstitial osmolality at the tip of the papilla is about nine times that of the cortex, whereas at the junction between outer and inner medulla, it is only about twice that of the cortex [31]. It is conceivable that this high gradient is generated in the inner medulla by the recycling of urea from the pelvic urine. Gertz, Schmidt-Nielsen and Pagel [32] using perfusion experiments in the renal pelvis, found that urea passes back from the pelvis to the tissue of the mammalian renal medulla and that water exchanges rapidly between the pelvic urine and medulla. In mammalian kidneys, urea accumulation in the medulla plays an important role in the concentrating mechanism [33]. The theory behind the relationship of the structure of the mammalian renal pelvis and the urine concentrating ability of the kidney has also been advanced by Pfeiffer [9] who stated that urea could be recycled form the pelvic urine to the renal medulla with consequent building up of osmotic concentration in the medulla. This facilitates water movement and urine concentration. The efficiency of this mechanism entails a large surface area of the pelvic-medullary interface; this is typically presented by the kidney of the camel as revealed by the present study. The bovine kidney has no pelvis, and so the major calyces in this species empty directly into the ureter [28]. It is interesting to note that due to the lack of a renal pelvis in bovine, urea could not be recycled and this may be one of the reasons why the bovine kidney is not noted for the production of concentrated urine. The extensive three dimensional arrays of fornices (recesses collaterales) provided by the renal pelvis furnishes a large surface area in contact with the numerous medullary pyramids. Up to 36 pyramids converge from the dorsal, ventral and lateral regions of the kidney as revealed by dissection and corrosion casts (Figures. 1, 3, and 4). In the Bacterian camel [34] stated that "the medulla was composed of 11 or 12 renal pyramids". This is far less than those presently found in the kidney of the dromedary camel. The medullary pyramids are situated within the recesses collaterales (fornices) in contact with the pelvic urine. The walls of the collateral recesses extend from the

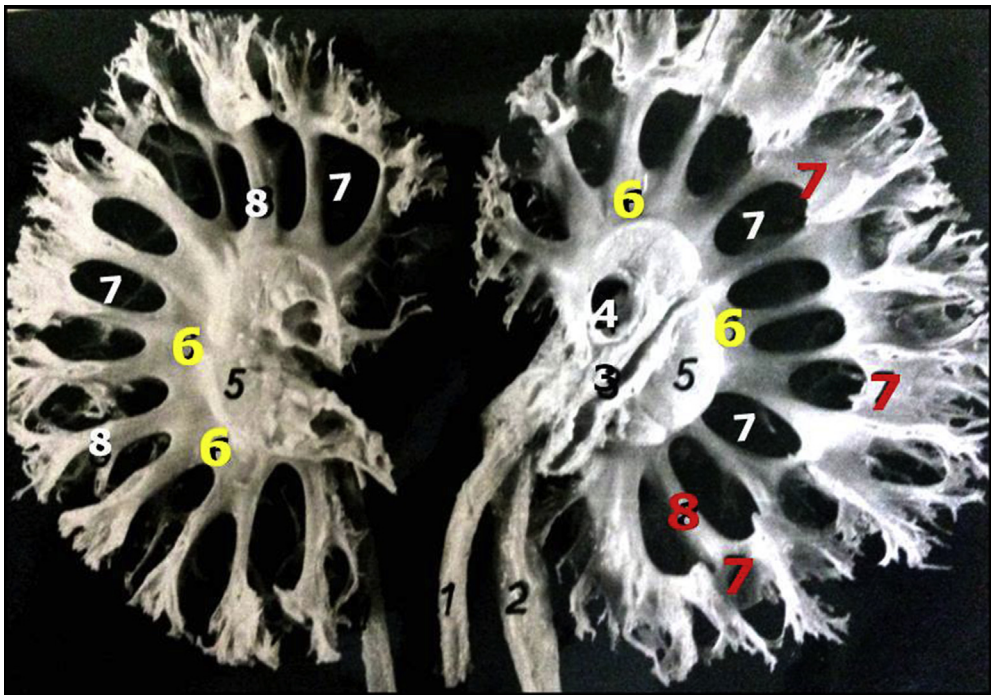

Figure 3. Renal pelvis of the right kidney of the camel obtained by dissection and removal of the kidney tissue piece by piece and then divided into dorsal and ventral halves to expose the internal view. 1, renal artery; 2, renal vein; 3, ureter; 4, stump of renal vein; 5, fat padding in the renal sinus; 6, main cavity of renal pelvis; 7, holes for convergence of about 36 renal pyramids from dorsal, ventral and lateral regions of the kidney to form the renal crest within the main cavity of the renal pelvis(6); 8, walls of collateral recesses housing the interlobar renal vessels and separating the holes for the passage of renal pyramids (See also Figure 1).

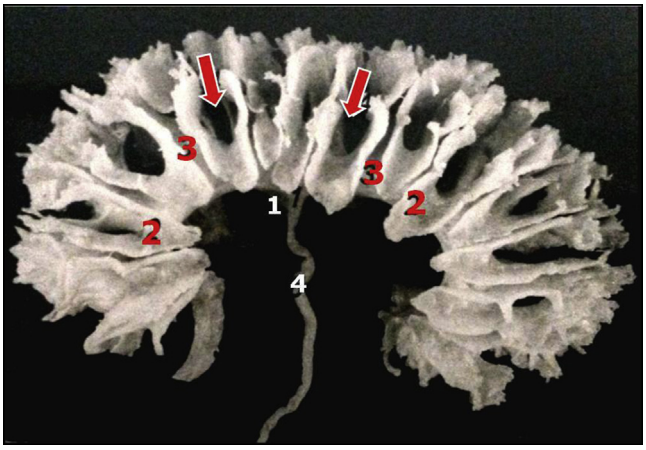

Figure 4. Dorsal view of a vinylite corrosion cast of the renal pelvis of the camel obtained by injection of 10% polyvinyl chloride through the ureter showing the recesses collaterales (fornices) of the renal pelvis. These recesses increase the surface area of contact between the pelvic urine and the renal pyramids for recycling of urea to increase the osmotic concentration in the medulla; water will then be drawn into the medulla thereby contributing to urine concentration. 1, junction of ureter with renal pelvis; 2, *recesses collaterales* (fornices of the pelvis); 3, grooves for walls of collateral recesses. Arrows indicate the holes for the passage of the renal pyramids between the recesses; 4, ureter (Compare with Figure 3).

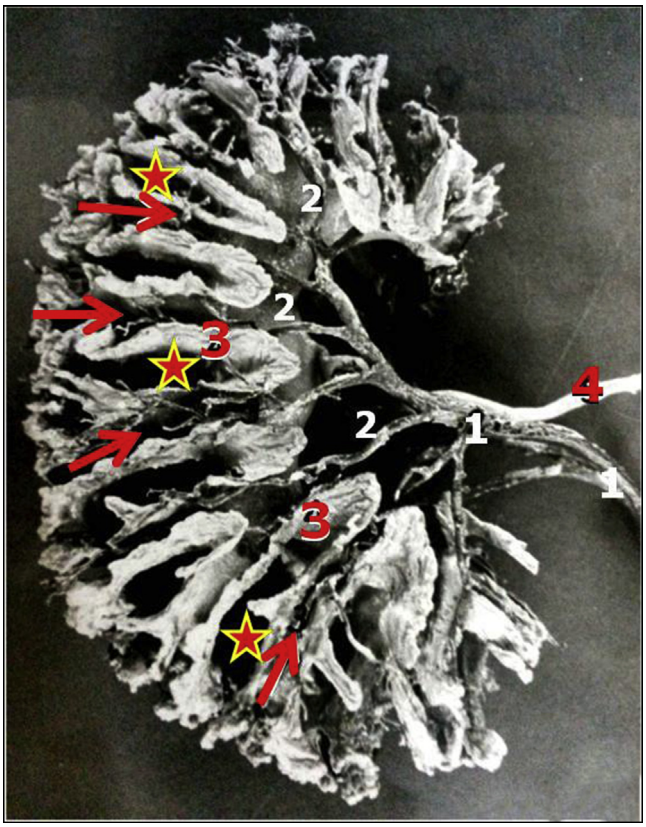

Figure 5. Vinylite corrosion cast of the renal pelvis of the camel and the renal artery obtained by injection of 10% polyvinyl chloride showing the relationship between the interlobar branches of the renal artery and the recesses of the pelvis. Arrows indicate the grooves for walls of collateral recesses 1, renal artery; 2, interlobar arteries; 3, recesses of renal pelvis; 4, ureter; asterisks, holes for passage of renal pyramids.

renal sinus and house the interlobar renal vessels (Figure 5). Furthermore, the surface area for water and urea movement is augmented by the extensive surface of the renal crest projecting into the large main cavity of the renal pelvis (Figure 2). The surface of the renal crest (inner medulla) is in contact with the urine in the main pelvis, and the surfaces of the medullary pyramids are in contact with urine in the recesses collaterales. This large pelvic-medullary interface is lined by simple low cuboidal epithelium (Figure 6) which enhances the recycling of urea and water from the pelvic urine into the medulla and directly contributes to urine concentration. On the other hand the rest of the wall of the renal pelvis and its recesses facing away from the pelvic-medullary interface is lined by transitional epithelium which is impermeable to water and urea. This epithelium virtually covers the connective tissue of the renal sinus and its columns that intervene between the recesses and house the interlobular branches of the renal vessels (Figures. 5 and 6). Furthermore, underneath the cuboidal epithelium, the inner medulla where urea is recycled consists of vasa recta, thin segments of loop of Henle and collecting ducts (Figure 6). These structures are responsible for the counter-current mechanism for urine concentration. Also it is conceivable that the rate of exchange of solutes and water between the pelvic urine and the vasa recta is augmented by the large surface area provided by the fornices. This strongly suggests that the renal pelvis of the camel with its extensive fornices plays a role in urine concentration and water conservation. However, urea production shows no correlation to the size of the renal pelvic urinary space [33, 35].

The other morphometric parameters required in the kidney of the camel for the production of concentrated urine and water conservation have been discussed in our previous report [11].

The enzyme alkaline phosphatase is known to function in membrane transport and reabsorption [22, 36, 37] especially glucose and hence water. Therefore this enzyme is expected to prevail in the kidney of the camel if this organ is destined to contribute to urine concentration and water conservation. More than 80% of the water entering the glomerulus is reabsorbed by the proximal convoluted tubule [27]. The present study demonstrates for the first time intensive alkaline phosphatase activity in the proximal convoluted tubules of the camel. Both paraffin and cryostat

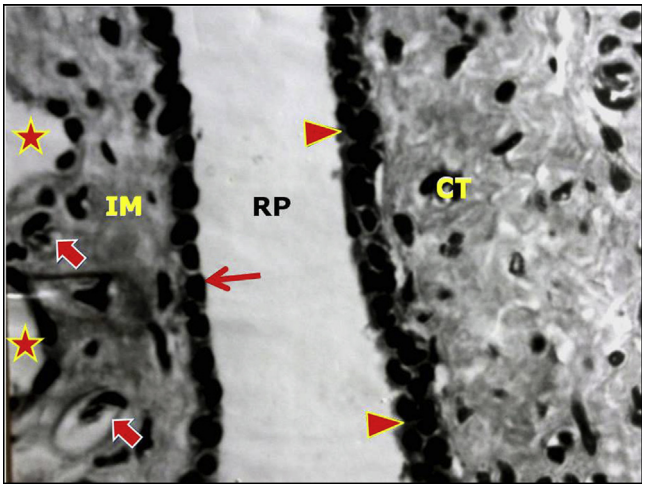

Figure 6. Photomicrograph of an H&E section of the kidney of the camel in the region of one of the collateral recesses (RP) of the renal pelvis Each collateral recess has two surfaces: the surface covering the connective tissue (CT) of the wall of the recesses, lined by transitional epithelium (arrowheads), and the surface covering the inner medulla (IM) of the renal pyramid lined by simple cuboidal epithelium (arrow), which allows the recycling of urea and water and urine concentration. Thick red arrows indicate vasa recta in the inner medulla; asterisks, thin limbs of loop of Henle. X466.

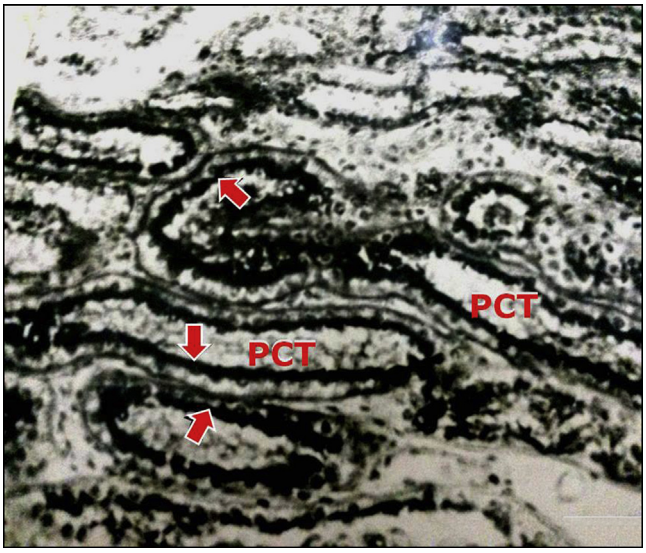

Figure 7. Photomicrograph of a section of the kidney of the camel showing intense activity of alkaline phosphatase (arrows) in the brush border of the proximal convoluted tubules (PCT). The enzyme is involved in membrane transport. Gomori calcium method. X240.

sections showed high activity of alkaline phosphatase in the brush border of the cortical proximal convoluted tubules. The enzyme was found in large amounts as judged by the extent and intensity of the reaction (Figure 7). This indicates the first step in water conservation by the kidney of the camel and emphasizes the role of alkaline phosphatase activity in reabsorption, though no other part of the nephron shows activity of this enzyme. However, although histochemical demonstration of alkaline phosphatase is precise and adequate, more quantitative measurements of this enzyme in the kidney of the camel and specific assays are required for unequivocal statement.

Regarding the role of antidiuretic hormone, it has been stated [1] that the maximum concentration of the urine depends on the capacity of the kidney to withhold water not on increased secretion of antidiuretic hormone. Nevertheless, the physiological role of the antidiuretic hormone in water conservation should be investigated in the camel. These findings coupled with our previous morphometric analysis of the kidney of the camel [11], lead to the conclusion that the kidney of the camel has all the anatomical and histochemical requisites for the production of concentrated urine. These requisites enable the kidney to contribute to the ability of the camel to conserve water and withstand the aridity of its habitat.

4. Conclusion

The present study demonstrated that the camel's kidneys are well suited for the production of concentrated urine. This could be used as an animal model, which helps understanding water conservation in mammals. The main cavity of renal pelvis of the camel is cresentic in shape and follows the long axis of the kidney. The renal crest is formed by the converging renal medullary pyramids and projects into the cavity of the renal pelvis. Elaborate three dimensional recesses extend from the main cavity of the renal pelvis towards the medulla and house the medullary pyramids before they join to form the renal crest. The crest and the medullary pyramids are covered by permeable low cuboidal epithelium. This intimate relationship of the renal pelvis and the medullary tissue facilitates the recycling of urea and water from the pelvic urine into the medulla and further concentrate the urine. In addition to these features, the intense activity of alkaline phosphatase in the proximal convoluted tubules revealed in this study strongly suggests transport across the tubular membrane.

Declarations

Author contribution statement

M. Abdalla: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

I am greatly indebted to the technical staff of the Department of Anatomy, Faculty of Veterinary Medicine, University of Khartoum for their assistance.

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