CHAPTER

1

Structure of Kidneys and Urinary System

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STRUCTURE OF KIDNEYS AND URINARY TRACT

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i. Location and Relationship

Kidneys are a pair of bean-shaped organs situated obliquely in the retroperitoneum on either side of the vertebral column extending from the 12th thoracic vertebra to the 3rd lumbar vertebra. The upper poles are normally oriented more medially and posteriorly than the lower poles. The adult kidney measures approximately 11.5 × 6.5 × 3.5 cm and weighs about 150 g each. The right kidney is at a lower level than the left due to interposition of the liver between the kidney and the diaphragm. Left kidney is slightly longer and narrower than the right kidney (Fig. 1.1). In some cases,

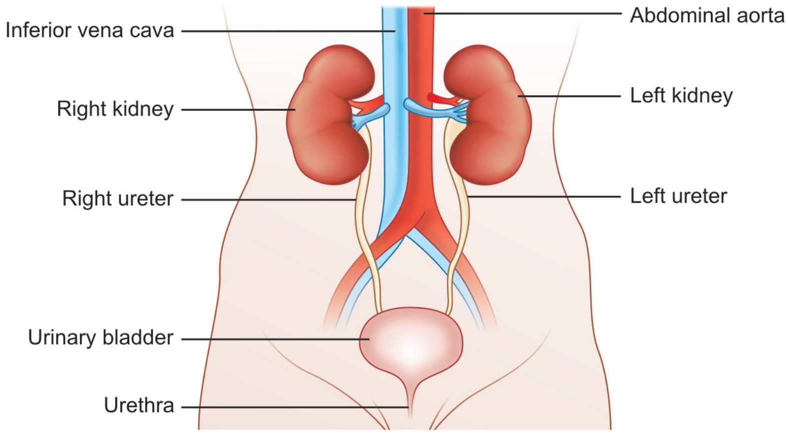
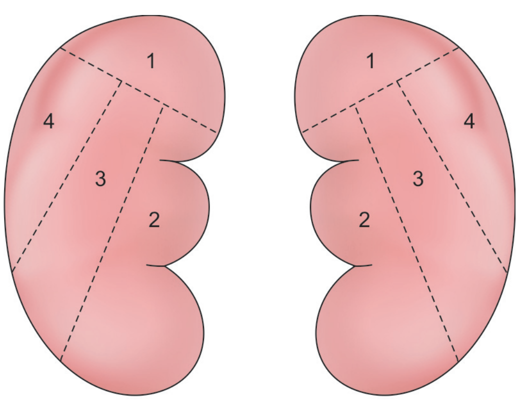


Fig. 1.1: Location of kidneys

the left kidney may have a hump-like projection on the lateral border, called "dromedary hump". Kidneys are highly vascular and receive one-fifth of the total cardiac output under normal conditions.

The upper one-third of the posterior surface of both kidneys is in contact with the diaphragm. The lower two-thirds are related to psoas major, quadratus lumborum and transversus abdominis muscles on both sides (Fig. 1.2). The 11th and 12th ribs lie behind the diaphragm posterior to the adrenal glands and upper poles of the kidneys bilaterally. Any injury that produces fracture of lower ribs, especially posteriorly, must be evaluated for potential renal injury as well. The kidneys move during inspiration due to the descent of the diaphragm. Since the pleura and the lower ribs lie more superficial to the diaphragm, removal of the lower ribs during renal surgery may injure the pleura.

Medially, the kidney is in relation to the inferior vena cava. The left kidney is related anteriorly to spleen, stomach, tail of the pancreas, splenic flexure of the large intestine and jejunum. The left suprarenal gland is situated superomedially at the upper pole of the kidney. The right kidney is related anteriorly to the liver. Suprarenal gland is closely related to its upper pole. During operations on the kidney, unless proper care is taken any of the above structures can be injured. Because of its close relation to the gastrointestinal system, kidney diseases may present with misleading gastrointestinal symptoms.



1. Diaphragm
2. Psoas major
3. Quadratus lumborum
4. Transverse abdominis

Fig. 1.2: Posterior relationship of kidneys

Kidneys are supported by the perirenal fat, the renal vascular pedicle, abdominal muscle tone and the general bulk of the abdominal viscera. The average vertical mobility of the kidney on inspiration or on assuming upright position is 4–5 cm (one vertebral body height). This mobility may be restricted or absent when the kidneys are fixed as in perinephric infections and malignancies. Occasionally the kidneys may be excessively mobile (floating kidney, mobile kidney).

At birth, the kidneys measure approximately 4.5 cm in length and are irregular in contour with multiple lobulations called 'fetal lobulations' which usually disappear in the first year of life. The kidneys and adrenals are larger relative to the body size in children. Because of relative larger size, mobility and lesser amount of perinephric fat, kidneys are more susceptible to injury in children.

ii. Surface Marking and Gross Anatomy

The kidneys can be mapped out by the *Morris parallelogram*. Draw two horizontal lines passing through D11 and L3 spine. Two vertical lines are drawn 2.5 cm and 9.5 cm each from the median plane. The hilum of the kidney is marked opposite the lower border of L1 spine. Kidneys are drawn with the long axis oblique so that the upper poles are nearer and lower poles are farther from the median plane. (Fig. 1.3).

Ureters can be marked by joining the following points on the back. Mark a point at the lower border of L1 vertebra, 4 cm from the midline. The second point is at the dimple overlying the posterior superior iliac spine. Joining these two points give the surface marking of ureter.

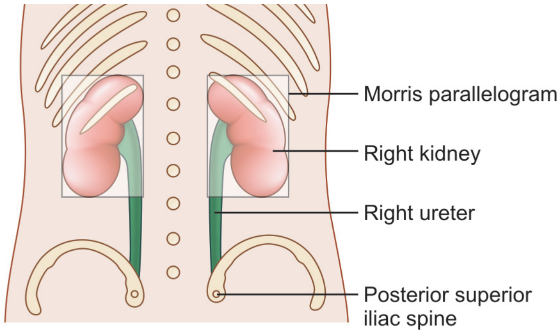


Fig. 1.3: Surface marking of kidneys

Each kidney has an upper pole, a lower pole, an anterior surface, a posterior surface, a convex lateral border and a concave medial border. The upper poles are closer to the midline than the lower poles aligning with the lateral border of the psoas muscle. The kidney is covered by a tough fibrous capsule which can be easily peeled off the surface of the kidney. In renal infections, it becomes adherent to the kidney. Outside this capsule and the perinephric fat, is the fascia of Gerota. It has an anterior layer and a posterior layer. Since the layers fuse on all the sides except at the inferior pole, any perirenal fluid collection tracks only downwards. The concave medial border has a slit-like aperture through which the renal vessels, nerves and pelvis traverse and is called the "renal hilum". The hilum communicates with a flattened space inside the kidney called the "renal sinus". It is filled with fat, through which the pelvicalyceal system, blood vessels, nerves, lymphatics enter or leave the kidney. These structures produce the 'central echogenic complex' on ultrasound. The renal pelvis branches into major and minor calyces in the renal sinus.

On longitudinal cut section, the kidney has 3 distinct parts, the cortex, the medulla and the pelvicalyceal system. The cortex is the outermost part which is homogenous and dark red in color. It is about 2–3 cm wide and contains the glomeruli, tubules, blood vessels and the interstitium. The medulla contains the loop of Henle, the vasa recta, and the collecting ducts in addition to interstitial space called the "renal medullary interstitial space". The renal medulla can be further subdivided into outer zone adjacent to cortex and inner zone that includes papilla. The outer zone of medulla is subdivided into inner and outer stripe representing the location of various segments of renal tubules. The inner medulla is slightly paler and consists of 8–18 conical masses called renal pyramids and intervening cortical tissue called renal columns of Bertin. The base of the pyramid is at the corticomedullary junction. The tip of the pyramid called the "papilla" extends into the renal sinus and is capped by the funnel-shaped minor calyx. There are two types of papillae: Simple papillae and compound papillae. The upper and lower poles usually contain compound papillae. Compound papillae are prone for intrarenal reflux and scars due to vesicoureteral reflux. Such scars are commonly seen at the poles. The minor calyx collects the urine drained from the kidney into the extrarenal collecting system.

The innermost region in the pelvicalyceal system is a hollow space lined by transitional epithelium. The spaces between the pyramids are called minor and major calyces. The minor calyces are cup-like structures collecting urine from the papillae. They join to form three or four major calyces which in turn unite to form the renal pelvis. Renal pelvis is the funnel-shaped expanded upper portion of the ureter that drains urine into the urinary bladder (Fig. 1.4).

iii. Nephron Structure

The nephron is the basic functional unit of the kidney. There are approximately 1 million nephron in each kidney. The nephron consists of an ovoid renal or malpighian corpuscle (comprised of the glomerulus and Bowman's capsule) and a hollow tubule of approximately 50 mm length that drains into the collecting duct system. The different segments of the nephron are as follows (Fig. 1.5).

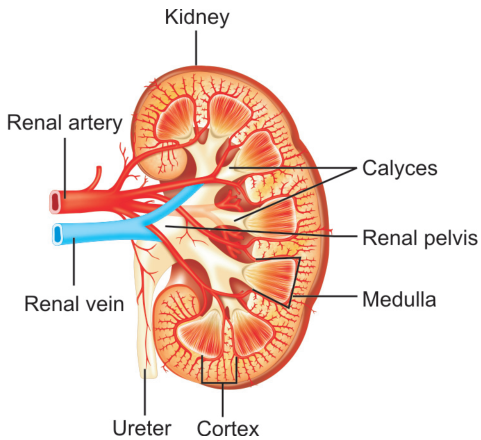


Fig. 1.4: Longitudinal cut section through kidney at hilum

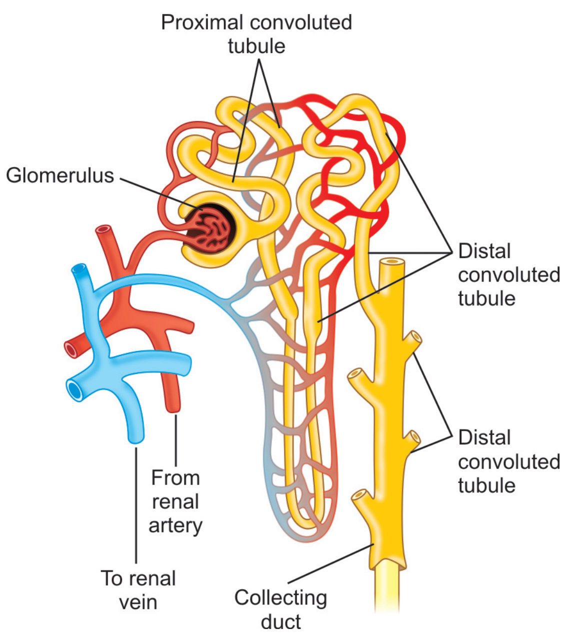


Fig. 1.5: Nephron—the functional unit of kidney

- Glomerulus and Bowman's capsule
- Proximal convoluted tubule
- loop of Henle (LOH)
- Distal convoluted tubule
- Collecting duct (which opens into the renal papilla)

The glomerulus is formed by the invagination of the bulbous, blind proximal end of the nephron by the afferent arteriole forming the tuft of capillaries in the Bowman's space. Glomerulus filters blood across Bowman capsule into the proximal convoluted tubule. It is approximately 200 µm in diameter and has a central skeleton, consisting of glomerular mesangial matrix and mesangial cells surrounded by the glomerular capillaries, the basement membranes and the epithelial cells. The capillary network is lined by a thin layer of fenestrated endothelial cells. The glomerular basement membrane is composed of a central dense layer, the lamina densa, an outer lamina rara externa and an inner lamina rara interna. The Bowman's capsule is lined on the inside by visceral epithelial layer and on the outside by the parietal cell layer. The urinary space is in-between two epithelial cell layers. The visceral epithelium is continuous with the parietal epithelium at the vascular pole, where the afferent arteriole enters and the efferent arteriole exits the glomerulus. At the urinary pole, the parietal cell layer is modified and continues as the proximal tubular cell.

The visceral epithelial cell or podocyte is the largest cell within the glomerulus. Podocyte has a main cell body containing the nucleus and cytoplasmic extensions, which divide, forming small finger-like processes that interdigitate with similar structures from adjacent cells and cover the capillaries. These interdigitations have numerous projections called 'foot processes' which rest on the basement membrane of the glomerular capillaries. The space between adjacent foot processes is known as the filtration slit. The adjacent foot processes are joined together by a thin membrane known as the slit-pore diaphragm. As the blood flows through the glomerulus, an ultrafiltrate of plasma is produced. The filtration barrier is composed of the fenestrated endothelium, glomerular basement membrane (GBM), and the slit pores between the foot processes of the visceral epithelial cells (Fig. 1.6).

The proximal tubule (PCT) consists of an initial convoluted portion, the pars

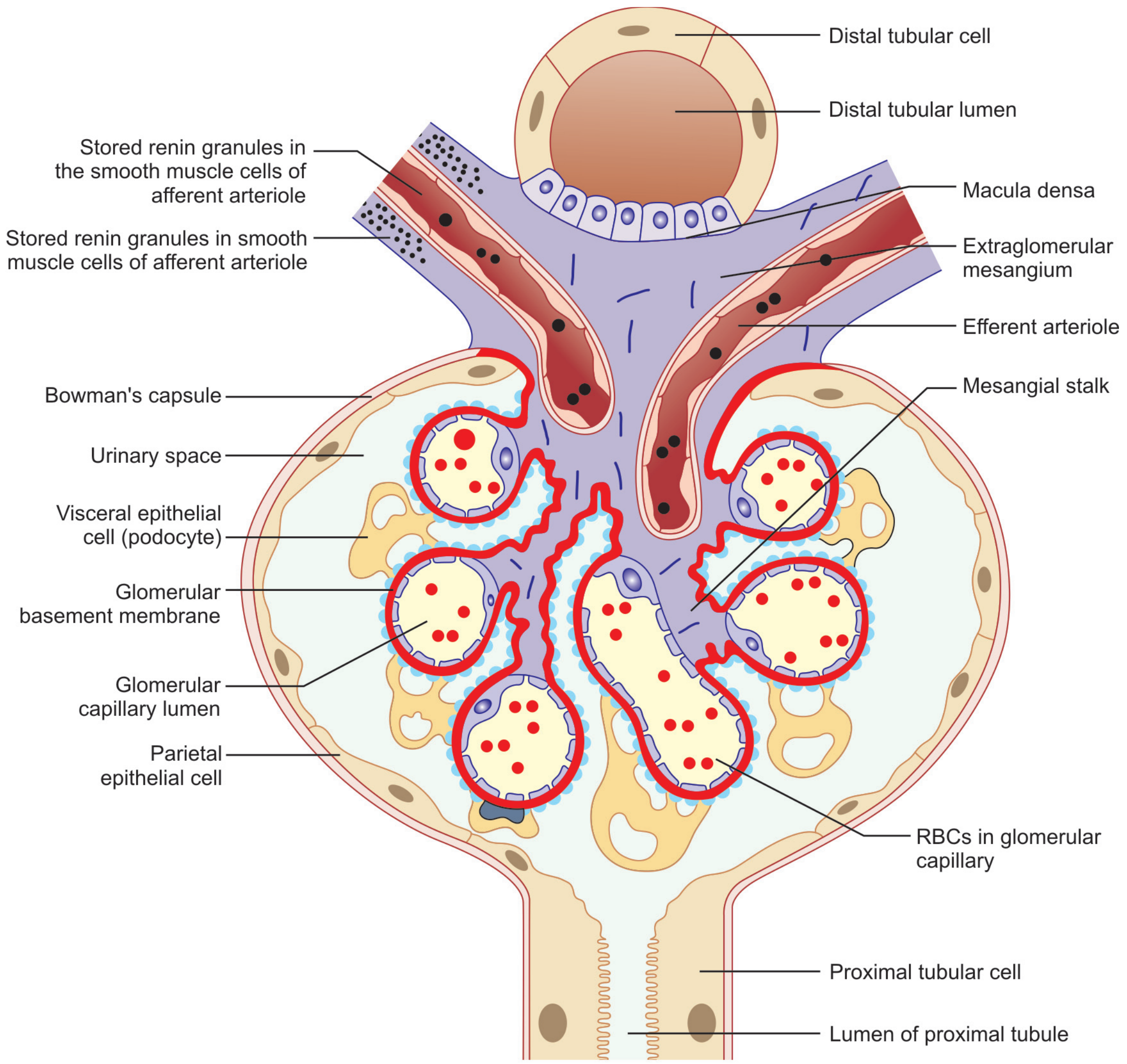


Fig. 1.6: The glomerulus

convoluta, located in renal cortex and a straight portion, the pars recta, located in the outer stripe of outer medulla. The portion of the cortex which contains the straight portions of proximal and distal tubules and collecting duct is called 'medullary ray'. The PCT is lined by metabolically active cuboidal cells that contain a number of cellular organelles like mitochondria. The luminal aspect of the proximal tubular cell has minute finger-like projections giving the appearance of a brush border.

The loop of Henle (LOH) is a U-shaped bend in the nephron. The straight segment of the proximal tubule ends as a narrow tube lined by flattened cells. This is the thin descending limb of LOH and it travels from the corticomedullary junction towards inner medulla where it forms the loop. The thin limb continues in the reverse direction towards the corticomedullary junction for a variable distance as thin ascending limb. In the outer medulla, the cells become cuboidal and form the thick ascending limb and proceed to the cortex.

The distal tubule is composed of continuation of thick ascending limb of LOH (pars recta), the macula densa, the distal convoluted tubule (pars convoluta) and the connecting tubules. The lining cuboidal cells here do not contain as many cellular organelles or brush border as the proximal tubular cells. The pars recta traverses the cortex within the medullary ray after which, the distal tubule comes in contact with the afferent arteriole and glomerulus of the same nephron. Here the afferent arteriolar cells and the distal tubular cells become modified to form the juxtaglomerular apparatus (JGA) (Fig. 1.7). The arteriolar smooth muscle cells contain secretory granules which are precursors of renin and distal tubular cells become modified as tall columnar and "macula densa" cells with chloride sensing receptors. The supporting mesangial cells within the JGA are called the "lacis cells".

The pars convoluta is the convoluted segment of the distal tubule which continues as connecting tubule and represents a transitional region between the distal tubule and the collecting duct. The collecting duct also traverses through the medullary ray towards the tip of the papilla. It is sub-divided into the cortical collecting duct, the outer medullary collecting duct, and the inner medullary collecting duct depending on the region traversed by it. The cells of the collecting duct are of two types, principal cells and intercalated cells. The collecting ducts open on the surface of the papilla as slit-like openings. This arrangement prevents reflux of urine from the caly to collecting tubule.

The renal interstitium is composed of interstitial cells and a loose, flocculent extracellular matrix. There are two types of interstitial cells—type 1 interstitial cell resembling fibroblast and type 2 interstitial cells resembling mononuclear cells or lymphocytes. Type 1 cells have a stellate appearance and contain an irregularly shaped nucleus and a well-developed rough- and smooth-surfaced endoplasmic reticulum. These cells synthesize erythropoietin.

iv. Zones in the Kidney and Relationship to Nephron Segments (Fig. 1.8)

Depending on the location in the renal cortex, nephrons are classified into superficial, mid-cortical and juxtamedullary nephrons. The glomerulus, proximal and distal tubules lie in the cortex. The loop of Henle, and part of the collecting ducts are located in the medulla. The juxtamedullary nephrons have very long loops of Henle that traverse the entire medulla. The outer stripe of the outer medulla contains the terminal straight segments of proximal tubule, the thick ascending limbs and collecting ducts. The segments in the inner stripe of outer medulla include thick ascending limbs, descending thin limbs and collecting ducts.

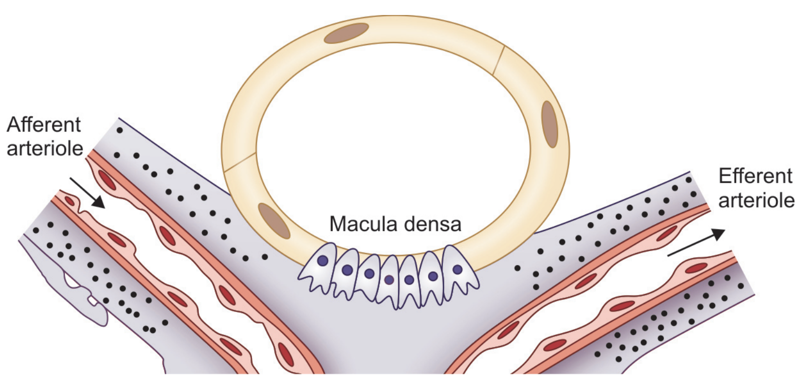


Fig. 1.7: Juxtaglomerular apparatus

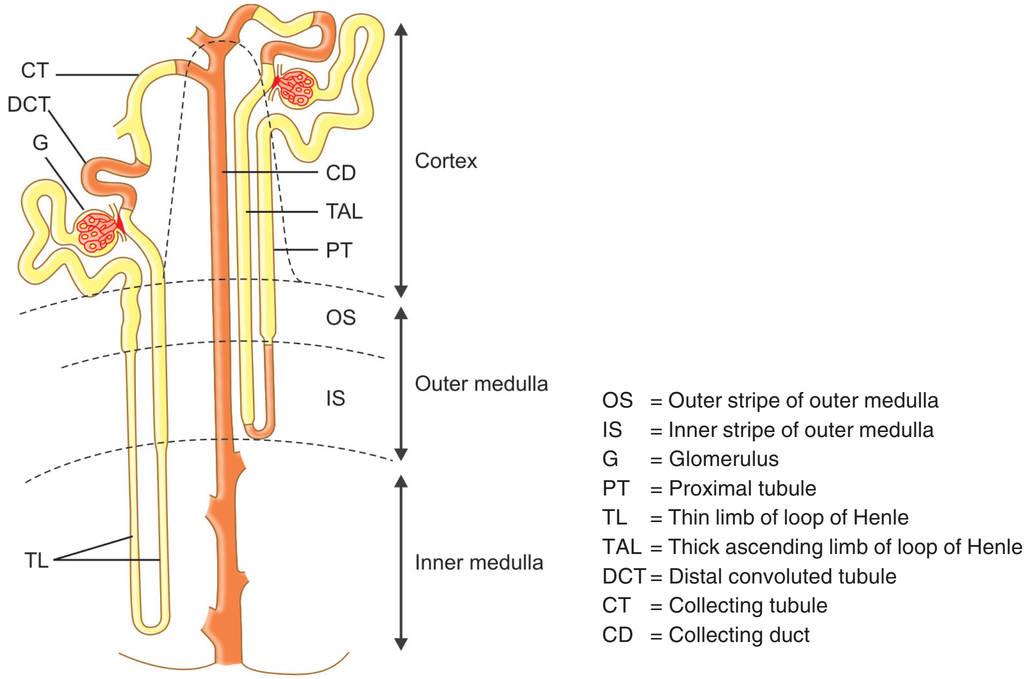


Fig. 1.8: The nephron in relation to zones in renal cortex and medulla

The inner medulla contains both descending and ascending thin limbs and the collecting ducts. The osmolality of the inner medulla is maintained very high (about 1200 mOsm/kg) by the countercurrent mechanism (Fig. 1.9). The location of various segments of tubules in their respective cortical and medullary zones is of utmost importance in maintaining the concentration gradient and maximally concentrating the urine by the countercurrent system.

v. Renal Circulation, Lymphatics and Nerve Supply

Kidneys are highly vascular and receive one-fifth of the total cardiac output under normal conditions. Renal artery arises from the abdominal aorta and enters the kidneys through the real hilum. It divides into about 6–8 interlobar arteries which pierce the renal medulla to reach the corticomedullary junction. Here, they divide into a number of

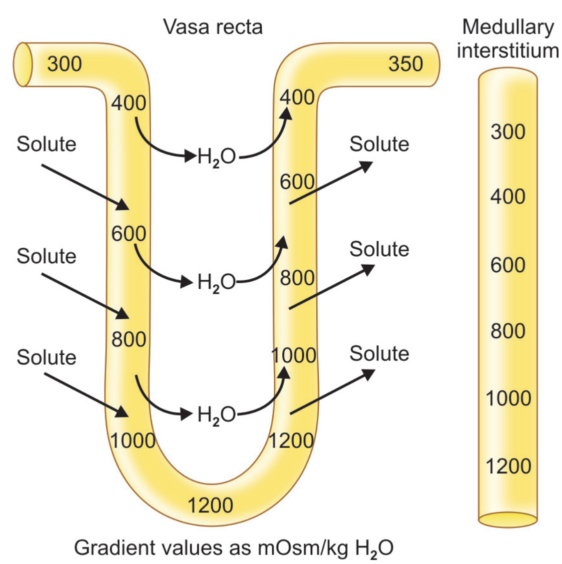


Fig. 1.9: Changes in osmolality along the nephron and various parts of renal interstitium

arcuate arteries which travel in all the directions from the point of origin at the corticomedullary junction like the spokes of an open umbrella. From the arcuate arteries, interlobular arteries arise and traverse the renal cortex perpendicularly and give rise to afferent arterioles. The afferent arteriole enters the Bowman's capsule and forms the capillary network. The efferent arterioles which come out of the cortical glomeruli form a peritubular capillary network and join to form interlobular vein, arcuate vein, interlobar vein and renal vein. The efferent arterioles coming out of the glomeruli near the corticomedullary junction (the juxtamedullary glomeruli), form long thin vasa recta which accompany the LOH in the renal medulla (Fig. 1.10). The descending vasa recta accompanies the ascending limb of LOH and vice versa. This has importance in the countercurrent mechanisms. These ultimately join the interlobular vein and drain into the renal vein. The renal arteries are end arteries and obstruction can lead to infarction of the corresponding area of the kidney. In contrast to this, there are plenty of communications between the intrarenal veins. Since the inferior vena cava is to the right of the aorta, the right renal vein is shorter than the left. The right renal vein usually does not have any branches, whereas the left renal vein receives adrenal, inferior phrenic and 2nd lumbar veins. At the hilum of the kidney, the renal pelvis is posterior, renal artery is in the middle and the renal vein is anterior.

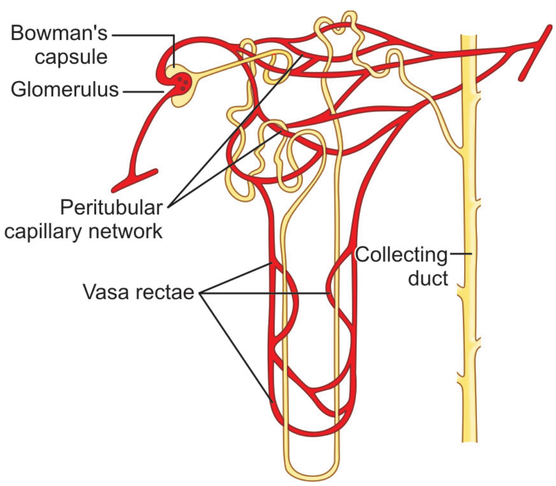


Fig. 1.10: Renal circulation

The lymphatics from the area near the renal capsule communicate with the lymphatics of the perirenal fat and periureteral sheath. The lymphatic channels from the renal cortex and medulla emerge at the hilum to end in the lymph nodes around the aorta and inferior vena cava.

The nerve supply to the kidney is from the plexus of nerves around the aorta which enter the kidney with the renal artery and innervate the vascular system and calyces. The renal capsule and pelvicalyceal system are the only two pain sensitive structures in the kidney.

vi. Microscopy and Ultrastructure

Under light microscope glomeruli and tubules can be seen. The glomerular capillary loops will be thin and delicate. Endothelial and mesangial cells and epithelial cell number together will be 2–3 per capillary loop. The surrounding tubules will be arranged in a back to back fashion with a little interstitium seen in between the tubules. Under electron microscopy, it will be possible to identify the cells, the fenestrations in the endothelium, the layers of basement membrane, the foot processes of the visceral epithelial cells and help to study the changes in various disease conditions.

vii. Structure of Ureter, Urinary Bladder and Urethra

The ureters are long muscular conduits, transporting urine from the renal pelvis to the urinary bladder. They are composed of helically arranged smooth muscle fibers. The transport of urine down the ureter is by the peristaltic waves that have been generated in the pacemaker cells of the minor calyces. The ureters traverse through the bladder musculature and submucosa obliquely. The oblique course and the firm underlying detrusor support prevent the reflux of urine into the ureters. The ureters are lined by transitional epithelium.

The urinary bladder is hollow muscular organ, storing urine at a low pressure of 5– 10 cm of water. This low pressure allows for continuously receiving urine from the ureters and storing the same. When about 400–600 ml of urine accumulates in the bladder, the individual gets an urge to void. If the circumstances are appropriate, voiding occurs with a flow rate of about 20–25 ml/second. If the circumstances are inappropriate, the urge to void can be suppressed. Normal voiding is complete with no residue at the end of micturition. Urinary bladder is composed of smooth muscles called detrusor. They are arranged in a haphazard fashion except at the bladder neck where the detrusor is arranged to form the proximal smooth muscle sphincter (internal sphincter). At rest, the proximal sphincter plays the major role in retaining the urine. This sphincter is ablated during prostatectomy and the continence is maintained by the distal skeletal muscle sphincter at the membranous urethra (the external sphincter). The voluntary initiation of micturition is by relaxation of the levator ani muscle. The urinary bladder is lined by transitional epithelium which has 3–7 layers. More than 7 layers are seen in urothelial malignancies.

The male urethra is about 20 cm long. It is divided into posterior urethra and anterior urethra by the urogenital diaphragm. The posterior urethra consists of prostatic and membranous urethra, whereas the anterior urethra consists of bulbous urethra and penile urethra. In the membranous urethra and distal prostatic urethra, special skeletal muscle fibers are present. These constitute the distal sphincter (rhabdosphincter). Though composed of skeletal fibers this sphincter is also involuntary. The posterior urethra, distal anterior urethra and the intermediate urethra are lined by transitional, squamous and pseudostratified columnar epithelium respectively.

The female urethra is about 4 cm long. The distal sphincter in females is weak. The proximal urethra is lined by transitional and distal urethra by squamous epithelium.