Renal Physiology — Renal Clearance, Tubular Transport and the RAAS

The kidney's physiology is an extremely complex issue in medicine, which is, therefore, a popular topic in exams. Since the kidney fulfills many important functions in the body in addition to its function as an excretory organ, it can be referred to as a multifunctional organ. The physiology of the kidney derives from the circumstances of its anatomical structures, especially those of the nephrons.

Apart from its well-known function as an excretory organ of the body, the kidney fulfills many important purposes in order to maintain a fully functional organism. Complete renal failure leads to death. The duties of the kidneys include:

- Excretion of urine
- Blood pressure regulation – The Renin-Angiotensin-Aldosterone System (RAAS)
- Homeostasis of the acid-base balance
- Regulation of water and electrolyte metabolism
- Hormone production

Glomerular Filtration

In order to understand the principle of glomerular filtration, it is important to first be aware of the anatomical structure of the kidney, especially the nephrons. Each kidney has an afferent arterial and efferent venous vasculature, as well as a uriniferous tubular system. Each nephron consists of a glomerulus and a tubule.
The operating principle is simple at first: the filtration process takes place in the glomeruli. The serum is expelled from the glomerular capillaries due to the effective filtration pressure. Thus, primary urine or ultrafiltrate is produced and accumulates within the Bowman capsule. From here primary urine flows inside a sequence of tubules. Vessels run alongside the tubules, and substances absorbed from the tubules enter these vessels. Conversely, substances can actively be removed from the peritubular capillaries and secreted into the tubules. This means that the composition and volume of the primary urine are not equal to that of the final urine!
The **glomerular filtration rate GFR** indicates the volume of primary urine filtered in the glomerulus per time unit. It is often expressed as ml/min and lies around 85 – 135 ml/min in healthy kidneys. It is quoted in standardized terms with reference to 1.73 m² of the body surface area. In many **kidney diseases**, its measurement is important as a parameter of kidney function, as decreased GFR can become very dangerous for the organism.

<table>
<thead>
<tr>
<th>Flow amount per minute (ml)</th>
<th>Calculation</th>
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</thead>
<tbody>
<tr>
<td>Renal blood flow</td>
<td>1050</td>
</tr>
<tr>
<td>Renal plasma flow</td>
<td>578</td>
</tr>
<tr>
<td>Glomerular filtration rate</td>
<td>110</td>
</tr>
<tr>
<td>Urine</td>
<td>1296 ml/day</td>
</tr>
</tbody>
</table>

| Renal blood flow | $1050 = 5000 \times 0.21 = 1050 \text{ ml blood/min}$ |
| Renal plasma flow| $578 = 1050 \times 0.55 = 578 \text{ ml plasma/min}$ |
| Glomerular filtration rate | $110 = 578 \times 0.19 = 110 \text{ ml filtration/min}$ |
| Urine | $1296 \text{ ml/day}$ |

Multiply urine/min with 60 minutes and with 24 hours to obtain daily urine production. $0.9 \times 60 \times 24 = 1296 \text{ ml/daily urine}$

**Table:** "Calculating Urine Formation per Day" by Phil Schatz. License: [CC BY 4.0](https://creativecommons.org/licenses/by/4.0/)

A driving pressure gradient is important for the filtration process. This **effective filtration pressure** $P_{\text{eff}}$ is the sum of various components. The first component is the capillary blood pressure $P_{\text{cap}}$ of around 48 mmHg, direct from the blood towards the filter. The second component is the pressure in the Bowman’s capsule $P_{\text{bow}}$ of around 13 mmHg, which acts in the opposite direction.

The third component is the colloid-osmotic or oncotic pressure $\pi_{\text{cap}}$ of about 25 mmHg, which is due to plasma proteins that cannot pass through the filter thus attracting water and ions out from the Bowman capsule and toward the blood. This results in: $P_{\text{eff}} = P_{\text{cap}} - P_{\text{bow}} - \pi_{\text{cap}} = 48 - 13 - 25 = 10 \text{ mmHg}$.

$\pi_{\text{cap}}$ increases sharply along the capillary because as water is removed from the blood, protein concentration raises. Once it reaches a value of 35 mmHg, $P_{\text{eff}}$ drops to 0 and the **filtration equilibrium** is reached, which means filtration does no longer occur. If the renal blood flow increases, the point of the filtration equilibrium is shifted further towards the end of the capillary and a longer segment of the glomerular capillary can be utilized for filtration. Thus **GFR depends on renal blood flow**. When the blood flow to the kidneys is reduced, such as heart failure or renal artery stenosis, the filtration must, therefore, be increased in order to perform the normal tasks of the kidney in balancing fluid and electrolytes in the body. This would be reflected by a high filtration fraction, showing that the kidneys have to do more work with the fluid they are receiving.
Renal Clearance

The concept of renal clearance arises from the function of the kidney as an organ of detoxification. It describes the amount of plasma volume which is completely cleared of a particular substance per time unit. Here other paths in addition to filtration are at play, such as absorption (removed from the tubules and transferred to the blood) and secretion (removed from the blood and transferred to the tubule) or excretion, or passage through and out of the tubule and into the collecting duct.

The amount of a substance in the tubular lumen increases through:

- Secretion
- Formation of new products of metabolism
- Glomerular Filtration

The amount of a substance in the tubular lumen decreases through:

- Absorption
- Excretion
- Metabolic degradation

The formula which is used for the clearance $C$ is $= K_{urine} \times V_{urine}/K_{plasma}$ which refers to the concentrations in urine and in plasma and the volume flow of urine.

Clearance can be used to determine the GFR, and thus the renal function. For this purpose, a substance has to be found that is neither secreted nor absorbed, is not metabolized but freely filtered. Inulin meets these requirements. If a patient is infused with inulin and then plasma and urine concentration of inulin are measured, the
clearance can be calculated and the GFR can be surmised. The following applies: inulin clearance curve = GFR.

GFR determination using inulin is very laborious. For routine checks and follow-ups, determination using creatinine clearance is usually sufficient. Its presence in plasma is relatively constant, except during high muscle activity. In case of a drop in GFR, the creatinine concentration in the plasma increases. Unfortunately, there is a so-called blind area. In some cases, creatinine concentration in plasma may only rise by 20% after significant reductions of GFR.

The concept of fractional excretion (FE) or clearance ratio is also noteworthy. It describes the fraction of the excreted amount in relation to the filtered amount per time unit, i.e. clearance of a substance X/inulin clearance. Therefore, FE = 1 applies for or inulin and creatinine. For substances that are absorbed in the tubule lumen FE <1 and for substances which are secreted FE > 1. An example of a very high fractional excretion is para-aminohippurate (PAH). It can have a FE of 5, ie 500%. It is actively secreted and thus excreted extremely fast.

Absolute urinary excretion can be distinguished from fractional excretion. Absolute excretion refers to the actual excreted volume of a substance in a 24 hours collection of urine, whereas fractional excretion (of sodium FE\textsubscript{Na}) is the percentage of the sodium filtered by the kidney which is excreted in the urine. It is measured in terms of plasma and urine sodium, rather than by the interpretation of urinary sodium concentration alone, as absolute urinary sodium concentrations can vary with water reabsorption. An example of how useful is FENa in the care of a critically ill patient is as follow: A sick, elderly patient has no urinary output for 24 hours. Is the patient in acute renal failure, has a post-renal problem or low in blood volume from dehydration (a pre-renal problem)?

\[ \text{FENa} = 100 \times \frac{\text{spot urinary sodium}}{\text{plasma creatinine}} \times \frac{\text{plasma sodium}}{\text{spot urinary creatinine}} \]

<table>
<thead>
<tr>
<th>Value</th>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>below 1%</td>
<td>prerenal disease</td>
<td>the physiologic response to a decrease in renal perfusion is an increase in sodium reabsorption to control hyponatremia, often caused by volume depletion or decrease in effective circulating volume (e.g. low output heart failure).</td>
</tr>
<tr>
<td>above 2% or 3%</td>
<td>acute tubular necrosis or other kidney damage (postrenal disease)</td>
<td>either excess sodium is lost due to tubular damage, or the damaged glomeruli result in hypovolemia resulting in the normal response of sodium wasting.</td>
</tr>
<tr>
<td>intermediate</td>
<td>either disorder</td>
<td>In renal tract obstruction, values may be either higher or lower than 1%. The value is lower in early disease, but with kidney damage from the obstruction, the value becomes higher.</td>
</tr>
</tbody>
</table>

**Clinical application of creatinine**

- Breakdown product of skeletal muscle
- Constant release into bloodstream: released in rate proportional to muscle mass
- Renal handling: freely filtered across glomerulus; not reabsorbed; slightly secreted
- Creatinine clearance (CCr): because of slight secretion CCr is slightly greater
than GFR; used as an approximation of GFR in practice

Do clinicians routinely measure creatinine clearance? Rarely, because it requires a timed urine collection, it is generally considered a nuisance. Instead, we typically use plasma creatinine concentration as a surrogate marker of creatinine clearance and, therefore, of GFR.

- Basic idea: \( Cr \approx \frac{1}{GFR} \) or \( GFR \approx \frac{1}{Cr} \)
- Very roughly, a “normal” \( Cr \approx 1 \) and a normal \( GFR \approx 100 \text{ ml/min} \)
- \( Cr \) of 2 implies a \( GFR \) that is half-normal, or roughly 50 \( \text{ ml/min} \)
- \( Cr \) of 3 implies a \( GFR \) in range of 33 \( \text{ ml/min} \)
- \( Cr \) of 4 implies a \( GFR \) of roughly 25 \( \text{ ml/min} \)

But, because \( Cr \) and \( GFR \) are inversely proportional, an increase in \( Cr \) from 1 to 2 represents a much more significant drop in renal function than an increase from 4 to 5.

- \( Cr \) rise of 1 to 2 implies a 50 % drop in \( GFR \) of 100 → 50 \( \text{ ml/min} \)
- \( Cr \) rise of 4 to 5 implies a 20 % drop in \( GFR \) of 25 → 20 \( \text{ ml/min} \)
- A \( Cr \) of 4 or 5 are almost clinically equivalent (i.e., both really bad)

Recall that as \( GFR \) drops, a greater proportion of \( Cr \) is excreted by secretion (rather than filtration). As \( GFR \) drops, creatinine clearance or any estimate of \( GFR \) based on \( Cr \) becomes less accurate.

**Creatinine clearance (CCr) of 24-hour urine collection**

Correlates with GFR

- Annual decrease in \( C_{cr} \) of 1 ml/min after age 50 years
- Useful in detecting renal dysfunction

\[
C = \text{Clearance} \quad | \quad U = \text{Urine (mg/dl)}
\]

\[
C_{cr} = \frac{U_{cr} \cdot V_{cr}}{P_{cr}}
\]

\( V = \text{Volume (ml/min)} \quad | \quad P = \text{Plasma (mg/dl)} \)

**Normal adult** \( C_{cr} \) **is 97 to 137 \text{ ml/min}**. In general, \( C_{cr} < 100 \text{ ml/min} \) is abnormal. \( C_{cr} < 10 \text{ ml/min} \) indicates renal failure. Elderly patients normally have a decrease in \( C_{cr} \). It is important to calculate the dose and dose interval for drugs that are nephrotoxic (e.g., aminoglycosides) in order to avoid precipitating acute renal failure due to nephrotoxic acute tubular necrosis.

**Causes of increased and decreased \( C_{cr} \)**

<table>
<thead>
<tr>
<th>Cause</th>
<th>Discussion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Increased ( C_{cr} )</strong></td>
<td></td>
</tr>
<tr>
<td>Normal pregnancy</td>
<td>Normal increase in plasma volume causes an increase in the GFR leading to an increase in ( C_{cr} ); highest at the end of the first trimester</td>
</tr>
<tr>
<td>Early diabetic glomerulopathy</td>
<td>Efferent arteriole becomes constricted due to hyaline arteriosclerosis causing an increase in the GFR and ( C_{cr} )</td>
</tr>
<tr>
<td></td>
<td>Increased GFR damages the glomerulus (hyperfiltration injury)</td>
</tr>
</tbody>
</table>
Elderly people
GFR normally decreases with age causing a corresponding decrease in the Cr\text{\textsubscript{e}}; danger when using nephrotoxic drugs

Acute and chronic renal disease
ARF due to acute tubular necrosis, CRF due to diabetic glomerulopathy

**Experimental calculations of renal function**

Renal Blood Flow:

- **RBF** = renal Plasma Flow + Non-plasma blood
- **RBF** = RPF/(1-Hct)
- **RPF** = Clearance of substance completely cleared in a single pass
- **RPF** = Clearance of PAH

Filtration Fraction = \( \frac{\text{GFR}}{\text{RPF}} \)

- **FF** = \( \frac{\text{C}_{\text{inulin}}}{\text{C}_{\text{PAH}}} \)
- **FF** = 15-20%

**Renal blood flow**

Compared to other organs in the body, the kidney is very heavily supplied with blood. Each minute, about 1.2 l blood pass through it (25% of our blood volume). This is referred to as **renal blood flow (RBF)**. However, most of it only reaches the cortex, which makes sense in terms of filtration, which takes place in the glomeruli, heavily packed in the cortex. O\textsubscript{2} consumption is directly linked to ATP-dependent Na\textsuperscript{+}-resorption.

Renal blood flow can be determined by measuring the above-mentioned PAH. Since **PAH is filtered freely and strongly secreted**, it can be assumed that the **renal plasma flow RPF** corresponds to the PAH clearance. Because about 90% of PAH is excreted (filtered plus secreted), \( \text{RPF} = V_x \times \frac{U_{\text{PAH}}}{(0.9 \times P_{\text{PAH}})} \).

To calculate the RBF from the RPF, the hematocrit can be used. Accordingly, the following equation results: \( \text{RBF} = \frac{\text{RPF}}{(1-\text{Hct})} \). Determination of the renal blood flow can be useful in many diseases.

The blood flow of the kidneys can autonomously be controlled by the kidneys themselves, called **renal autoregulation**. RBF is kept constant at a mean arterial pressure of 80 - 170 mmHg. This is attributed to an increase in renal flow resistance. GFR also remains constantly within this range.
### Table: "Paracrine Mechanisms Controlling Glomerular Filtration Rate" by Phil Schatz. License: CC BY 4.0

<table>
<thead>
<tr>
<th>Change in GFR</th>
<th>NaCl Absorption</th>
<th>Role of ATP and Adenosine/role of NO</th>
<th>Impacts on GFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased GFR</td>
<td>Tubular NaCl increased</td>
<td>ATP and adenosine increased, which leads to vascular constriction</td>
<td>Vascular constriction slows down the GFR</td>
</tr>
<tr>
<td>Decreased GFR</td>
<td>Tubular NaCl decreased</td>
<td>ATP and adenosine decreased, which leads to vasodilatation</td>
<td>Vasodilatation increases GFR</td>
</tr>
<tr>
<td>Increased GFR</td>
<td>Tubular NaCl increased</td>
<td>NO increased, which leads to vasodilatation</td>
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</tr>
<tr>
<td>Decreased GFR</td>
<td>Tubular NaCl decreased</td>
<td>NO decreased, which leads to vasoconstriction</td>
<td>Vasoconstriction decreased GFR</td>
</tr>
</tbody>
</table>

Two principles can be attributed to autoregulation: **myogenic response or Bayliss effect** and **tubuloglomerular feedback**. The myogenic response is defined as vasoconstriction of the interlobular arteries with increasing pressure. Thus, the increase in blood pressure ordinarily does not affect the afferent arterioles of the glomerulus.

The part of the kidney responsible for tubuloglomerular feedback is the **macula densa**, which lies between the distal tubule and the glomerulus. If high amounts of NaCl flow past the macula densa in the distal tubule, filtration in the glomerulus is limited by a reduction of RBF or GFR via the release/withhold of ATP/adenosine or NO.

## Tubular Transport

The tubular system, which joins the glomerulus, consists of the proximal tubule, descending limb, loop of henle, ascending limb, and the distal tubule, followed by the **collecting duct** and the **papillary duct, that ends in the renal papilla**. Molecules important for the body are resorbed along these systems, whereas harmful substances are secreted in order to be eliminated as quickly as possible.

Each section is equipped with specific transport proteins and channels that ensure the regulation of what is absorbed and secreted. Generally, tubular cells possess a **luminal side** toward the lumen and a **basolateral side** communicating with the bloodstream.
Proximal Tubule

The proximal tubule has a strongly defined brush border that creates a very large area, ideal for absorption of water and salt. In the first stage, sodium ions are resorbed and $\text{H}^+$ are ions secreted via a $\text{Na}^+-\text{H}^+$-exchanger, while glucose, galactose, amino acids, and other substances are resorbed through a $\text{Na}^+$-symporter. Through the transport of positive charge into the cells, a **lumenal negative transepithelial potential** is created.

Due to osmosis, substance transport causes water resorption through the relatively **leaky epithelium**. The water, in turn, drags dissolved molecules with it, a mechanism known as **solvent drag**. In the second stage, a lot of $\text{Cl}^-$ is resorbed after a quarter of the proximal tubule. Due to the negative charge of $\text{Cl}^-$, a **lumen positive transepithelial potential** arises. This results in paracellular resorption of cations.

The basolateral side has numerous $\text{Na}^+/\text{K}^+$ ATPases. Thus, sodium is repeatedly removed from the equilibrium of the cell. An electrical and chemical gradient is built up, which is crucial for the regulated transport. It is also important to note that aquaporins, small water channels, are built into both the luminal as well as the basolateral side for water transport.

Henle’s Loop

When studying Henle’s Loop it is particularly noteworthy that while water is absorbed in the descending part, NaCl is not. In the ascending section the exact opposite is the case: here, water absorption does not take place, but resorption of NaCl (and other ions) does. This is a crucial mechanism of urine concentration and an important task of Henle’s Loop.
In the luminal side of Henle’s Loop, certain Na\(^+\)-K\(^+\)-2Cl\(^-\)-cotransporters can be found. These carriers are targets for so-called loop diuretics, such as furosemide. The basolateral side contains specific Cl\(^-\)-transporters which can only be found in the kidney and the inner ear, and which contain a functional subunit, called Barttin.

The distal tubule

In the distal tubule, NaCl is resorbed. This takes place via a NaCl cotransporter that is sensitive to thiazide and aldosterone. While it can be inhibited by thiazides, it is stimulated by aldosterone. A Na\(^+\)/K\(^+\)-ATPase is embedded in the basolateral side of the distal tubule and maintains the gradient.

Tubular transport by nephron segment: proximal vs. distal nephron
### Proximal convoluted tubular mechanics

<table>
<thead>
<tr>
<th>Proximal</th>
<th>Distal</th>
</tr>
</thead>
<tbody>
<tr>
<td>• PCT</td>
<td>• Thick ascending limb</td>
</tr>
<tr>
<td>• Thin portion of loop of Henle</td>
<td>• DCT</td>
</tr>
<tr>
<td></td>
<td>• Cortical collecting tubule</td>
</tr>
<tr>
<td></td>
<td>• Medullary collecting duct</td>
</tr>
</tbody>
</table>

Proximal convoluted tubular mechanics

*Neither secreted nor reabsorbed; concentration increases as water is reabsorbed.

Tubular creatinine and inulin ↑ in concentration (but not amount) along the proximal tubule due to H₂O reabsorption. Cl⁻ reabsorption occurs at a slower rate than Na⁺ in the proximal 1/3 of the proximal tubule and then matches the rate of Na⁺ reabsorption more distally. Its relative concentration ↑ before it plateaus. Na⁺ reabsorption drives H₂O reabsorption, so it nearly matches osm.

**Correlation of nephron cotransporters and pumps with electrolyte disorders**

**Proximal renal tubule:**

A. Primary site for Na⁺ reabsorption:

(1) Na⁺ reabsorption is increased when cardiac output is decreased

   a) ↓ EABV → ↑ FF → P₀ > Pₜ
EABV = Effective arterial blood volume, FF = Filtration Fraction, Po = Peritubular capillary Oncotic Pressure, Ph = Peritubular Capillary Hydrostatic Pressure

b) Examples: congestive heart failure, cirrhosis, hypovolemia

(2) Na\(^+\) reabsorption is decreased when cardiac output is increased

a) ↑ EABV → ↓ FF → P\(_H\) > P\(_O\)

b) Examples: mineralocorticoid excess, isotonic gain in fluid

B. **Primary site for reclamation of bicarbonate (HCO\(_3^−\))**: Mechanism for reabsorbing some of the filtered HCO\(_3^−\) back into the blood.

(1) Hydrogen ions (H\(^+\)) in tubular cells are exchanged for Na\(^+\) in the urine

(2) H\(^+\) combines with filtered HCO\(_3^−\) to form H\(_2\)CO\(_3\) in the brush border of the proximal tubules

(3) Carbonic anhydrase (c.a.) dissociates H\(_2\)CO\(_3\) to H\(_2\)O and CO\(_2\). CO\(_2\) and H\(_2\)O are reabsorbed into proximal renal tubular cells.

(4) H\(_2\)CO\(_3\) is re-formed in the proximal renal tubular cells. H\(_2\)CO\(_3\) dissociates into H\(^+\) and HCO\(_3^−\)

(5) HCO\(_3^−\) is reabsorbed into the blood

(6) A Na\(^+\)/K\(^+\)-ATPase pump moves Na\(^+\) into the blood

**Decreased effective arterial blood volume**

**Increased effective arterial blood volume**
Thick Ascending limb of the Distal Tubule

Primary function is to reabsorb water separately from sodium. This increases osmolarity in the medulla via a counter-current mechanism (See below).

The collecting duct and the papillary duct

The so-called ENaC, an epithelial Na\(^+\) channel, is a membrane-bound ion-channel that is selectively permeable to Na\(^+\) ions and that is assembled as a heterotrimer composed of three homologous subunits α or δ, β, and γ. These subunits are encoded by four genes: SCNN1A, SCNN1B, SCNN1G, and SCNN1D. It is involved primarily in the reabsorption of sodium ions in the collecting ducts of the kidney's nephrons. It can be stimulated by aldosterone and ADH. It can be inhibited by amiloride, ANP and prostaglandins. Inflowing sodium from the lumen causes a lumenal negative potential, therefore K\(^+\) is secreted and Cl\(^-\) is transported paracellularly.

Here, the resorption of water is controlled by the antidiuretic hormone ADH. This hormone is released during water deficiencies and causes the incorporation of aquaporins in the luminal membrane. Resorption of water in the collecting duct is largely independent of sodium absorption.

Tubular secretion

A number of substances are secreted: organic cations and anions, including bile salts and uric acid. Substances being secreted enter the interstitial space from the peritubular capillaries. They are transported by organic transporters in basolateral membrane into the cytoplasm of tubular epithelial cells. They are transported out of cells and into tubular lumen by luminal membrane transporters.
Sites of drug action

1. Mannitol
2. Ca inhibitors
3. Loop diuretics
4. Thiazides
5. K⁺ sparing diuretics

Tubular secretion and diuretics

Most diuretics must gain access to tubular lumen to act. Most are highly protein-bound and are thus not freely filtered through the glomerulus. Transported into tubular lumen via organic ion transporters.

Clinical correlate

Loop diuretics are less effective in individuals with renal failure because other organic ions accumulate in renal failure and compete with diuretics for transport. Large doses of diuretics must be given to overcome this competition for tubular secretion.

Countercurrent Multiplier Theory

Henle’s Loop plays a crucial role in urine concentration. The countercurrent multiplier theory between Henle’s Loop and the vasa recta of the renal medulla is important here. The osmolality increases strongly in the direction of the loop apex. Through this corticomedullar gradient, water is withdrawn from the arterial blood flowing towards the apex, and this water is released back into the hyperosmolar venous vessels leaving the medulla.

Thus, a wash-out effect of the osmotic gradient at the apex of the loop in the renal medulla is avoided. The driving force of the countercurrent multiplier theory in Henle’s Loop is the active NaCl resorption in the ascending portion of the loop, in combination with a lack of water resorption due to the largely watertight epithelium.

Thus, the osmolality of the urine in the lumen of the ascending portion of Henle’s loop decreases, whereas the osmolality of the interstitium increases due to the inflowing NaCl. To compensate, water is resorbed from the descending part of the loop. Thus, the concentration of NaCl is highest at the apex of the loop, so that the resorption in the ascending part can take place passively.

This pumping system is kept in motion through a rolling principle called countercurrent multiplier theory. In the ascending, thick segment of the Loop of Henle, sodium is actively reabsorbed and discharged into the interstitium. This causes water reabsorption
in the descending part, increasing osmolarity of the urine.

The distal tubule and collecting duct concentrate the urine further, as strong resorption of water takes place here. This part is impermeable to urea. Urea can only be resorbed further down in the collecting ducts in the presence of ADH, and contributes to the total osmolality of the interstitium, which is crucial for the maintenance of the gradients.

The “single effect” theoretical approach to visualize the step-by-step of how the countercurrent multiplier is formed. Once the corticopapillary osmotic gradient is established, it can be modified but does not need to be reestablished.

The Renin-Angiotensin-Aldosterone System — RAAS

Granulosa cells of the juxtaglomerular apparatus produce the enzyme renin. It proteolytically cleaves angiotensinogen into angiotensin I, which is hydrolyzed by the angiotensin-converting enzyme (ACE) to angiotensin (Ang) II. A rise in ANG II leads to
the production of aldosterone in the cortex of the adrenal gland. The system serves to maintain blood pressure and can sense drops as small as 10-15mmHg. ACE is a target for ACE inhibitors, used for the treatment of elevated blood pressure.

Renal hormone production

In addition to renin, which is not a hormone in itself but affects hormone production, erythropoietin (EPO) is another important product of the kidney. It is a glycoprotein, which is formed in the endothelial cells of the capillaries. It affects the formation of red blood cells in the bone marrow and is released in case of hypoxia.

Pathophysiology

The Bartter syndrome

If one of the transporters in the ascending limb of Henle’s loop fails due to a loss-of-function mutation, the so-called Bartter syndrome takes place. Thereby, resorption of Na⁺, Mg²⁺, Cl⁻ and Ca²⁺ is disturbed. Although this can be partially or even completely reversed in later sections, it is associated with increased K⁺ and H⁺ secretion. Signs are Na⁺- and volume depletion, hypocalcemia, and hypokalemic alkalosis.

The Gitelman syndrome

A genetic defect in the transporter of the distal tubule leads to Gitelman syndrome. The clinical signs are similar to those of Bartter syndrome but milder.

The Liddle syndrome

Here, a gain-of-function mutation leads to a permanently open state of ENaC in the collecting ducts. This is accompanied by hypervolemia, hypertension, hypokalemia, and alkalosis and can be compared to symptoms of high aldosterone secretion, therefore it is also called pseudohyperaldosteronism.

Pseudohypoaldosteronism type 1

Pseudohypoaldosteronism presents the opposite clinical picture of Liddle’s syndrome. It is characterized by hypovolemia, hypotension, hyperkalemia, and acidosis and is based on a loss-of-function mutation of ENaC.

Diabetes insipidus

In diabetes insipidus, the antidiuretic hormone (ADH) is completely absent or has only limited effect. Thus, there is no incorporation of aquaporins in the collection tube, therefore the re-resorption of water is disturbed. This leads to a greatly increased urinary excretion of 5 to 25 L per day.

A distinction is made between diabetes insipidus centralis and diabetes insipidus renalis. The former is associated with damage of the pituitary gland or hypothalamus, which results in disruption of ADH production. In the second variant, ADH cannot function sufficiently due to defects in the region of the collecting tube.

Renal Tubular Acidosis (RTA or Necrosis, RTN)
Hypoxia or toxic drugs can produce selective damage to the proximal or distal tubule, causing loss of bicarbonate (damage to the proximal tubule) or loss of secretion of Hydrogen ions (damage to the distal tubule).

Review Questions

The solutions can be found below the references.

1. Which of the following is correct? The term renal autoregulation describes the ability of the kidney...

   A. ...to maintain the RBF and GFR in a certain range, regardless of the blood pressure constant.
   B. ...counteract a rise in blood pressure through vasodilation.
   C. ...to constrict the capillaries, in order to reduce the RBF.
   D. ...to decrease the GFR and RBF in an autoregulation range, when the blood pressure rises.
   E. ...increase the GFR and RBF in an autoregulation range, when the blood pressure drops.

2. The Renin-Angiotensin-Aldosterone System (RAAS) system serves blood pressure regulation. Which is most true? It works via...

   A. ...the splitting of ANG I to ANG II.
   B. ...the release of renin and the subsequent cleavage of angiotensinogen.
   C. ...the production of EPO and the possibility of increased oxygen transport.
   D. ...suppression of aldosterone production.
   E. ...natural inhibition of the angiotensin-converting enzyme with ACE inhibitors.

3. Renal clearance refers to...

   A. ...the amount of plasma volume completely cleared from a particular substance per time.
   B. ...the amount of the plasma volume completely cleared from all substances.
   C. ...the quantity of substances that can be removed from a determined volume of plasma per unit of time.
   D. ...the quantity of substances that are excreted in the urine per unit of time.
   E. ...the amount of plasma volume, which is excreted with the urine per unit of time.

References


**Correct answers:** 1A, 2B, 3A

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