Intracellular Potassium in Cells of the Distal Tubule

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Summary. Using a new double-barreled K+-selective liquid ion-exchange microelectrode effective intracellular [K+] and the peritubular PD were measured simultaneously in single cells of the distal tubule of the rat kidney. The transepithelial PD was measured in the same kidney. A mean [K+] of 46.5 ± 1.6 mM was obtained in the distal tubule cells of normal rats. The effective intracellular [K+] increased significantly to 60.5 ± 2.1 mM with chronic K+ loading and to 51.5 ± 0.9 mM with metabolic alkalosis, and decreased significantly to 36.5 ± 2.6 mM with chronic K+ depletion and to 38.7 ± 1.4 mM with metabolic acidosis. The luminal membrane PD was depolarized in the kaliuretic states of K+ loading and alkalosis and hyperpolarized in the kaliopenic states of K+ depletion and acidosis. Thus the summation of the observed chemical and electrical driving forces between the cellular and luminal compartments could quantitatively account for the passive entry of K+ into the lumen of the distal tubule under the different metabolic states.

Key words: Potassium Microelectrode — Liquid Ion-Exchange Microelectrode — Intracellular Potassium — Kidney Cell Potassium — Distal Tubule Cell Potassium.

Potassium is the major determinant of the electrophysiological properties of nephrons [4,15]. This paper describes a double-barreled K+-selective liquid ion-exchange microelectrode and its applications in measuring effective intracellular [K+] in single cells of the renal tubular epithelium of the rat kidney. The effective intracellular [K+] as measured by a direct electrometric method is certainly more meaningful than the total K+ content of the epithelial cells as measured by indirect chemical analyses. This report focussed on studying various states that may be associated with a change in effective intracellular potassium concentration.

In the rat kidney the K+ secretory process is localized in the distal convoluted tubule. Since the K+ secretory process in the distal tubule is determined by the magnitude of the effective rather than total intracellular potassium, the unexpectedly low values of effective [K+] in distal tubule cells has eliminated the need to postulate the presence of active potassium influx processes at both the peritubular and the luminal cell membranes.

This electrometric study of distal tubule cell K+ in various states that may be associated with a change in intracellular [K+], reveals that there
is a good correlation between K⁺ excretory rate and distal cell potassium. The luminal membrane PD was depolarized in the kaliuretic states of K⁺ loading and alkalosis and hyperpolarized in the kaliopenic states of K⁺ depletion and acidosis. Thus the summation of the observed chemical and electrical driving forces across the peritubular and the luminal cell membranes could quantitatively account for the passive transport of K⁺ across these two membranes under the different metabolic states.

**Methods**

*Electrometric Methods*

The process of constructing double-barreled K⁺ liquid ion-exchange microelectrodes follows the general guidelines outlined for the construction of the single-barreled micropipette [7]. Two segments of Pyrex capillary tubing, cemented together, are held over a microflame and at the softening point rotated 360° and pulled slightly. Then it is mounted in a vertical pipette puller and pulled into two double-barreled micropipettes with tip diameter of one micron or less. Fig.1 is a diagrammatic representation of the electrode.

The K⁺-selective liquid ion-exchanger (Coming Catalog No. 476132) is an organic electrolyte dissolved in an organic solvent. It is substantially insoluble in aqueous solutions. Its adhesiveness to non-siliconized glass surfaces is poor in comparison with water which can readily displace it. Therefore, the tip end of the shank of the exchanger (indicator) barrel is rendered hydrophobic-organophilic by siliconization with 1.25% silicone oil (Dow Coming 1107) in trichlorethylene. The tip of the reference barrel is not siliconized. Then the micropipettes are cured in an oven at 200°C for 2 h.

After siliconization the two barrels are filled separately with the ion-exchanger and reference salt solution by means of filler microcapillaries. The rest of the shank and the stem of the exchanger barrel is filled with 0.1 M NaCl. An Ag-AgCl wire is inserted into the stem of each barrel as an internal reference element.

The potential measurements were made by means of a pair of electrometers and the readings were displayed on a Grass polygraph. All equipment was placed inside a Faraday cage and grounded to a common copper bar. K⁺-microelectrodes were considered suitable for cellular measurements if they satisfied all the following criteria. A high K⁺ sensitivity exhibited by a response of 55—60 mV/decade change of K⁺ activity. A K⁺:Na selectivity coefficient of better than 40:1 in the concentration range of 10—100 mM (selectivity calibrations in both pure and mixed NaCl, KCl solutions). Only electrodes with a fast response time were used. A K⁺-microelectrode had a lag time of 18 msec, a time constant of 85 msec and a rise time (from 10% to 90% of final value) of 160 msec. Stability exhibited by a minimal drift of the potential of less than 1—2 mV per hour was required. Only microelectrodes with low tip potentials of less than 5 mV were used.

The accuracy of the double-barreled K⁺-microelectrode was evaluated by serial readings in solutions of pure KCl 1, 10, 100 and 200 mM and in different combinations of mixed solutions of KCl and NaCl. A mean ratio of potentiometric/analytical [K⁺] of 1.02 ± 0.03 (ratio not significant from unity) was obtained. Readings in a solution containing 100 mM KCl were reproducible to ± 0.1 mV.

*Renal Methods*

The studies were carried out on Sprague Dawley rats maintained on a normal diet, a high K⁺ diet (General Biochemicals, TD-71051) with 15% KCl added to it,
and a low K⁺ diet (General Biochemicals, No. 170550). The food was withdrawn 12–16 h before experiments. The 3 drinking regimens were: tap water, ammonium chloride 75 mM (metabolic acidosis) and sodium bicarbonate (metabolic alkalosis).

The rats were anesthetized with Inactin and placed on an electrically-heated table at 38°C. The conventional micropuncture methods were used. The left carotid artery was cannulated for blood sampling. The kidney was mounted into a concentric pair of plastic cups. Isotonic saline in 2% agar was poured over the kidney to fill the smaller, inner cup. A hole in the center of the agar was filled with warm mammalian Ringer ([K⁺] 4.3 mM). The extracellular reference micropipette was immersed into this solution.

Glomerular filtration rate was measured with the clearance of inulin carboxyl-14C. Urine acid plasma [K⁺] was measured by flame photometry; tubular fluid K⁺ by a dual-channel ultramicro flame photometer. The pH and PCO₂ of arterial blood and urine were measured by a Radiometer pH capillary electrode and a PCO₂ electrode.

The distal site transit time was measured using the lissamine green technique. As in a previous report [16], a correlation of distal site transit time with the definitive localization (neoprene cast technique) was made. Linear regression of transit time on % length distal tubule yielded \( y = 0.691x + 16.41 \) (correlation coefficient: \( r = 0.625, P < 0.001 \)).

Renal cortical slices were analyzed for extracellular space (inulin-¹⁴C), potassium (flame photometry) and after correcting for extracellular space, intracellular [K⁺] per kg cell water was calculated according to the method of Boyle et al. [1].

**Results**

The major concern in this study was localization of the tip of the double-barreled K⁺-microelectrode (Fig. 1) in the intracellular compartment of distal tubular cells. The leads of the two barrels were connected to one electrometer and this gave the K⁺ potential. The leads of the reference barrel and the external 3 M NaCl single barrel micropipette were connected to another electrometer and the PD between them represented the membrane potential. The potassium potential and the membrane potential were measured and recorded simultaneously on a Grass polygraph. In Figs. 2a and 2b the upper tracing is the membrane potential; the lower the K⁺ potential. Thus the membrane and the K⁺ potentials are both electrometric determinations with the reference barrel half-cell common to both.

![Diagram of double-barreled K⁺-selective liquid ion-exchange microelectrode](image-url)
The double-barreled electrode was mounted on an Electrode Carrier connected to a Hydraulic Micro-Drive (David Kopf, model 1207S). The Electrode Carrier itself is mounted on a Leitz micromanipulator. Initially, the tip of the double-barreled K⁺-microelectrode and the single-barreled micropipette are immersed in Ringer solution covering the kidney. The tip of the K⁺-microelectrode is advanced very close to the peritubular surface of an identified distal tubule segment, and subsequent advances are made in a stepwise fashion few micra at a time by using the remote control mechanism. As the double-barreled microelectrode enters the peritubular membrane, an abrupt steep rise in both the membrane potential (upper tracing) and the K⁺ potential (lower tracing) is recorded. The electrical profile of the peritubular membrane potential is characterized by a sharp peak followed by an exponential decay (Fig. 2a). The peak plateau of the cell K⁺ potential is several folds greater than the electrode response time of $\leq 0.2$ sec. In Fig. 2b after recording the peritubular membrane PD and the cell K⁺ potential, the double-barreled electrode was advanced a few micra into the lumen of a late distal tubule to register two stable potentials: a transepithelial PD of about 50 mV and a K⁺ potential equivalent to about 17 mM.
Frequent calibrations with flanking standards were made before and after cellular impalements. If the electrode potential in the calibrating standards or the overlying Ringer shifts significantly the electrode is changed. Changes in the tip potential of the reference barrel were usually the source of sudden shifts in potential. A number of measures were taken to minimize the movement and pulsations of the kidney itself. These included a double kidney cup system, a subdiaphragmatic disc and setting the kidney in an optimal position before pouring the agar.

Table 1 gives the macroscopic data for rats chronically maintained on normal, high and low K+ diets. Both the fractional (\(\%\)) and the absolute rates of K+ excretion changed markedly with the two experimental diets. Rats maintained on 75 mM sodium bicarbonate as a drinking regimen and given an infusion of 150 mM isotonic bicarbonate during the experiment excreted 61.7 ± 4.9\(\%\) of their filtered K+ and their K+ excretory rate was 38.3 ± 2.1 \(\mu\text{M/kg·min}\). Rats maintained on 75 mM ammonium chloride as a drinking regimen and given an infusion of 150 mM ammonium chloride during the experiment excreted 3.2 ± 0.2\(\%\) of their filtered K+ at an absolute K+ excretory rate of 0.73 ± 0.04 \(\mu\text{M/kg·min}\).

Table 2. Summary of distal tubule intracellular effective K+ concentration (electrometric) in 3 groups of rats maintained on a normal K+ diet, high K+ diet and low K+ diet

| Diet   | GFR (ml/min·kg) | [K+] plasma (mM) | \(\%\) filtered K+ excreted (\(\%\)) | K+ excretion rate (\(\mu\text{M min}^{-1}\cdot\text{kg}^{-1}\)) |
|--------|-----------------|------------------|----------------------------------|----------------------------------|
| Normal | 11.2 ± 1.3      | 4.3 ± 0.1        | 21.4 ± 3.2                       | 2.12 ± 0.04                     |
| High K+| 9.7 ± 1.8       | 5.2 ± 0.2        | 45.3 ± 3.6                       | 18.28 ± 1.22                    |
| Low K+ | 9.2 ± 2.1       | 2.9 ± 0.1        | 1.2 ± 0.1                        | 0.23 ± 0.01                     |

Table 2 gives a summary of the determinations of "effective" intracellular [K+] in single cells of the distal convoluted tubules of rats maintained on normal, high K+ and low K+ diets. The K+ potential was read as effective intracellular [K+] and not activity because we did not want...
to assume a value for the mean intracellular ionic activity coefficient as we do not know the ionic strength of distal cell cytoplasmic fluid. 94 determinations from different sites of the distal convoluted tubules of normal rats yielded a mean value of effective \([K^+]\) of 46.5 ± 1.6 mM. By comparison with normal rats, with chronic \(K^+\) loading the effective \([K^+]\) increases significantly \((P < 0.001)\) by 14 mM to a value of 60.5 ± 2.1 mM, and with chronic \(K^+\) depletion the effective \([K^+]\) decreases significantly \((P < 0.01)\) by 10 mM to a value of 36.5 ± 2.6 mM.

Thin cortical slices were obtained from 19 kidneys of 10 normal rats. The mean water content was 76.6 ± 0.5\% \(\text{of the wet weight}\). The extracellular space as determined by inulin\(^{14}\text{C}\) was 20.7 ± 1.2\% \(\text{of the wet weight}\). These slices were found to have a mean \([K^+]\) of 136.3 ± 4.2 mM per kg of kidney cell water. These results are in agreement with data obtained from mammalian kidney cortical slices by others [12].

Table 3 gives a summary of the determinations of the effective intracellular \([K^+]\) in single distal cells of rats with normal acid-base status, metabolic acidosis and metabolic alkalosis. By comparison with the normal state, with metabolic acidosis the effective \([K^+]\) decreases significantly \((P < 0.001)\) by 7.8 mM to a value of 38.7 ± 1.4 mM. With metabolic alkalosis it increases significantly \((P < 0.01)\) by 5 mM to a mean value of 51.5 ± 0.9 mM.

| Table 3. Summary of distal tubule effective intracellular \(K^+\) concentration (electro-metric) in 3 groups of rats: normal, metabolic acidosis and metabolic alkalosis |
|-----------------|-----------------|-----------------|
| Normal          | Acidosis        | Alkalosis       |
| \(\text{mean} \) (mM) | 46.5            | 38.7            | 51.5            |
| ± S.E.          | 1.6             | 1.4             | 0.9             |
| Number          | (94)            | (111)           | (167)           |
| \(P\)           | < 0.001         | < 0.001         |                 |

| Table 4. The mean values of the acid-base parameters of arterial blood and urine of rats with normal acid-base status, metabolic acidosis and metabolic alkalosis |
|---------------|---------------|---------------|
| **Blood**     | **Urine**     |               |
| pH (units)    | PCO\(_2\) (mmHg) | HCO\(_3^-\) (mM) | K\(^+\) (mM) | pH (units) | PCO\(_2\) (mmHg) | HCO\(_3^-\) (mM) | K\(^+\) (mM) |
| Normal 7.41   | 41.7          | 25.1          | 4.3 | 6.49 | 41.7          | 3.5 | 229.4 |
| ± S.E. (0.02) | (1.1)         | (1.6)         | (0.1) | (0.14) | (2.2)         | (1.1) | (31.4) |
| Acidosis 7.31 | 41.6          | 20.1          | 4.8 | 5.74 | 44.0          | 0.40 | 74.2 |
| ± S.E. (0.01) | (1.3)         | (0.9)         | (0.2) | (0.11) | (4.7)         | (0.15) | (31.0) |
| Alkalosis 7.53| 48.6          | 39.1          | 3.4 | 7.64 | 93.4          | 84.3 | 141.7 |
| ± S.E. (0.02) | (2.5)         | (1.1)         | (0.2) | (0.12) | (19.3)        | (12.2) | (41.6) |
Fig. 3. Cell \([K^+]\) against % length distal tubule. The equation of the least square line for cell \([K^+]\) as a function of % length is \(y = 0.084 x + 47.71\). The correlation coefficient of 0.15 is not significant.

Table 4 gives the mean values for the acid-base parameters of arterial blood and urine of rats with normal acid-base status, metabolic acidosis and metabolic alkalosis.

In the normal rats receiving isotonic saline at 2 ml/h, the 94 determinations of effective intracellular \([K^+]\) were done at different sites of the distal convoluted tubule to test if cellular \(K^+\) is a function of distal length. Fig. 3 is a plot of cell \([K^+]\) as a function of % length distal tubule. The equation for the least square line for cell \([K^+]\) as a function of % length is \(y = 0.084 x + 47.71\). The correlation coefficient of 0.15 is not significant. Therefore, cell \([K^+]\) is independent of distal tubule length. Others [5] have postulated a progressive increase in intracellular \([K^+]\) along the distal tubule to account for the increased \([K^+]\) of the more distal tubular fluid. Similarly, the peritubular membrane PD of distal tubules of normal rats was evaluated as a function of tubular length. For 67 determinations the equation for the least square line for the peritubular membrane PD as a function of % length was \(y = 0.06 x + 68.65\). The correlation coefficient of 0.20 is not significant. Therefore, the peritubular membrane PD is independent of distal tubule length.

Table 5 gives a summary of the determinations of membrane PD measurements under different metabolic states. The peritubular membrane PD did not change with the different metabolic states studied with
Table 5. Distal tubule PD (mV) measurements under different metabolic states. Values given represent the mean ± standard error

|                  | Normal     | High K⁺    | Low K⁺     | Acidosis   | Alkalosis   |
|------------------|------------|------------|------------|------------|-------------|
| Peritubular PD   | -67.4      | -68.5      | -65.7      | -49.0      | -67.5       |
| (measured)       | (± 1.0)    | (± 1.3)    | (± 1.2)    | (± 0.9)    | (± 0.9)     |
| Transepithelial PD| -47.1      | -62.2      | -18.8      | -14.2      | -52.7       |
| (measured)       | (± 1.6)    | (± 2.0)    | (± 1.0)    | (± 0.8)    | (± 1.3)     |
| Luminal PD       | -20.3      | -6.3       | -46.9      | -34.8      | -14.8       |
| (calculated)     |            |            |            |            |             |

the single exception of metabolic acidosis when its magnitude fell significantly ($P < 0.001$) from $-67.4 ± 1.0$ mV in normal rats to $-49.0 ± 0.9$ mV in rats with metabolic acidosis. The transepithelial PD (luminal negativity) was $-47.1 ± 1.6$ mV in normal rats. The lumen became significantly ($P < 0.001$) more negative with high K⁺ diet $-62.2 ± 2.0$ mV and with metabolic alkalosis $-52.7 ± 1.3$ mV ($P < 0.01$). The lumen became significantly ($P < 0.001$) less negative with low K⁺ diet $-18.8 ± 1.0$ mV and with metabolic acidosis $-14.2 ± 0.8$ mV. The luminal membrane PD represents the difference between the peritubular and transepithelial PD. As shown in Table 5 the luminal membrane PD was depolarized in the kaliuretic states of K⁺ loading and metabolic alkalosis and hyperpolarized in the kaliopenic states of K⁺ depletion and acidosis.

Discussion

The effective intracellular [K⁺] as measured by a direct electrometric method is certainly more meaningful than the total K⁺ content of cells as analyzed by indirect chemical methods. The effective intracellular [K⁺] of 46.5 mM in distal tubule cells represents about $1/3$ of the total K⁺ content (136 mM) of cells of renal cortical slices. From these values one may calculate an experimental activity coefficient for intracellular K⁺ ion of 0.34. If from this one were to conclude that only $1/3$ of the total tubular cell K⁺ may be free, this would contrast with nerve [6] and skeletal muscle [8] where measurements with K⁺ glass microelectrodes, showed that all the intracellular K⁺ is in free solution. However, whole cortical slices of the mammalian kidney contain both proximal and distal tubules. Therefore, strictly distal tubule cell K⁺ cannot be determined except by direct electrometric methods. In contrast, the amphibian kidney may be sliced to yield segments that are made of predominantly distal tubules. Analyzing kidney slices chemically, Sullivan [11] found a [K⁺] in distal cells of Amphiuma 97.5 mM while Whittembury et al. [13] found a [K⁺]
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Fig. 4. A representation of the electrochemical longitudinal profile along the length of the distal tubule

of 108 mM in the Necturus kidney. Our electrometric finding of a low K+ activity may be consistent with the observation of a low radio-kinetic K+ exchangeability in the Amphiuma kidney [14] and rat colonic mucosa [2].

Both cell K+ (Fig. 3) and the peritubular membrane PD are independent of distal tubule length. The increased luminal negativity of the second half of the distal tubule, first observed by Wright [16] generates a sufficient electrical driving force that can quantitatively account for the increased cell-to-lumen K+ influx to produce the observed luminal [K+] in the late distal tubule (Fig. 4). K+ diffusion from cell to lumen is a rapid process, i.e. diffusion is not the rate-limiting step.

In Fig. 4 the electro-chemical forces are given for accessible initial and final segments of the distal tubule. On the basis of a passive K+ distribution between the intracellular and luminal compartments, the predicted luminal [K+] is close to its measured value in tubular fluid both in the initial and terminal segment of the distal tubule. The fact that the measured [K+] of tubular fluid approaches the predicted value, suggests that K+ is approaching an equilibrium distribution between cell and lumen. This is in disagreement with previous calculations [9,10] which because of the assumed high value of cellular [K+] the predicted tubular fluid [K+] was always much greater than the measured value. Accordingly, a luminal membrane K+ reabsorptive pump was postulated.

Fig. 5 is schematic representation of K+ and Na+ transport in a late distal tubule cell. The [K+] in the late distal tubule lumen (17.2 mM) and distal cell (46.5 mM) were determined electrometrically.

The electro-chemical gradients across the peritubular cell membrane are uniform along the whole length of the distal tubule. At the peritubular cell boundary the measured membrane potential ($E_m$) of $-67.0 \pm 1.0$ mV
is significantly ($P < 0.001$) more negative than the calculated $K^+$ equilibrium potential ($E_K$) of $-60.7 \pm 0.9$. Therefore, $K^+$ ion can move passively down an electro-chemical potential gradient from the peritubular fluid into the cell. Having eliminated the need to postulate active $K^+$ influx, the peritubular cation pump need not be a coupled pump but may well be an electrogenic Na pump. The greater intracellular negativity, in addition to favoring passive $K^+$ entry into the cell also prevents $K^+$ leak from cell to peritubular fluid.

The electro-chemical gradients across the luminal cell membrane are not uniform along the length of the distal tubule (Fig.4). As shown in Fig.5, in the late distal tubule, the luminal membrane PD ($E_m$) of $-20.0 \pm 1.0$ is significantly ($P < 0.005$) less negative than the $K^+$ equilibrium potential ($E_K$) of $-24.5 \pm 0.9$, thus indicating the presence of a residual net electro-chemical driving force favoring $K^+$ passive secretion from cell to lumen. Sullivan [11] found that whereas the peritubular membrane of Amphimna distal tubule is predominantly permeable to $K^+$, the luminal membrane is essentially equally permeable to $K^+$ and Na$^+$. At the luminal boundary, while $K^+$ leaks passively from cell-to-lumen, Na$^+$ enters passively from lumen-to-cell. This represents a passive free cationic exchange phenomenon at the luminal cell membrane. Thus the distal tubule $K^+$ secretory process consists of 2 passive diffusion steps in series: from interstitium-to-cell and from cell-to-lumen.

This electrometric study has revealed that distal tubule cell effective $[K^+]$ is 46 mM. Since distal cell Na$^+$ is not likely to be all free, these epithelial cells may have an intracellular fluid whose osmolarity and ionic strength are of the same magnitude as the hypotonic and hypoionic tubular fluid bathing the luminal surface.
Table 6. Late distal tubule potassium concentration ratios, electrical potential differences, and calculated $K^+$ equilibrium potentials across the different boundaries of the distal tubular epithelium under different metabolic conditions

| Parameter                  | Normal | High $K^+$ | Low $K^+$ | Acidosis metabolic | Alkalosis metabolic |
|----------------------------|--------|------------|-----------|-------------------|--------------------|
| $[K^+]$ plasma             | 4.3    | 5.2        | 2.9       | 4.8               | 3.4                |
| (TF/P)$_{K^+}$             | 4      | 9          | 1.5       | 2                 | 7                  |
| $E_K$ (calculated)         | -35    | -55        | -10       | -18               | -49                |
| $E_{m}$ Transepithelial    | -47    | -62        | -19       | -14               | -52                |
| $[K^+]$ cell               | 46.5   | 60         | 36        | 39                | 52                 |
| (Cell/TF)$_{K^+}$          | 17.2   | 47         | 4.4       | 9.6               | 23.8               |
| $K^+$ excretory rate       | 2.12   | 18.28      | 0.23      | 0.73              | 38.3               |

The upper section of Table 6 deals with transepithelial ratios, thus ignoring the intensive properties of the tubular epithelium. With the exception of metabolic acidosis, the transepithelial PD ($E_{m}$) is more negative than the $K^+$ equilibrium potential ($E_K$). This implies that $K^+$ approaches but does not quite attain electro-chemical equilibrium distribution between the interstitial and luminal compartments. The correlation between $K^+$ excretory rate and plasma $[K^+]$ fails with states of acid-base imbalance.

The middle section of Table 6 is a summary of the intracellular-luminal interactions. There is a good correlation between $K^+$ excretory rate and distal cell $[K^+]$ in the different metabolic states studied. Tubular fluid $[K^+]$ does not correlate well with the $K^+$ excretory rate. The fact that the luminal membrane PD ($E_{m}$) is less negative or close to the $K^+$ equilibrium potential ($E_K$) indicates that $K^+$ distribution across the luminal cell boundary approaches that of an electro-chemical equilibrium.

The effective intracellular $[K^+]$ determines the chemical driving force for the passive $K^+$ leak from cell to lumen. The luminal membrane PD is an electrical force that opposes the leakage of $K^+$ from the cell. The two kaliuretic states of chronic potassium loading and metabolic alkalosis are characterized by an increase in the effective intracellular $[K^+]$ and a decrease (depolarization) of the luminal membrane PD. In contrast, the two kaliopenic states of chronic potassium depletion and metabolic acidosis are characterized by a decrease in the effective intracellular $[K^+]$. 
and an increase (hyperpolarization) of the luminal membrane PD. Thus the summation of the observed chemical and electrical driving forces between the cellular and luminal compartments could quantitatively account for the different rates of passive entry of $K^+$ into the lumen of the distal tubule in metabolic states which are associated with changes in the secretion, and therefore, excretion of potassium.

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