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Quantification of free water transport in peritoneal dialysis

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Background. In peritoneal dialysis (PD) total net ultrafiltration (NUF) is dependent on transport through small pores and through water channels in the peritoneum. These channels are impermeable to solutes, and therefore, crystalloid osmotic-induced free water transport occurs through them. Several indirect methods to assess free water transport have been suggested. The difference in NUF between a 3.86% and a 1.36% solution gives a rough indication, but is very time consuming. The magnitude of the dip in dialysate/plasma (D/P) sodium in the initial phase of a 3.86% exchange is another way to estimate free water transport. In the present study, a method was applied to calculate free water transport by calculating sodium-associated water transport in one single 3.86% glucose dwell.

Methods. Forty PD patients underwent one standard peritoneal permeability analysis (SPA) with a 1.36% glucose solution, and another with a 3.86% glucose solution. At different time points intraperitoneal volume and sodium concentration were assessed. This made it possible to calculate total sodium transport. By subtracting this transport (which must have occurred through the small pores) from the total fluid transport, free water transport remained. These results were compared with the other methods to estimate free water transport.

Results. For the 1.36% glucose dwell, total transcapillary ultrafiltration in the first hour ($TCUF_{0\text{-}60}$) was 164 mL, transport through the small pores was 129 mL, and free water transport was 35 mL (21%). For the 3.86% glucose solution, total $TCUF_{0\text{-}60}$ was 404 mL, transport through the small pores was 269 mL, and free water transport was 135 mL (34%). The contribution of free water transport in the first minute ($TCUF_{0\text{-}1}$) was 39% of the total fluid transport. From the 40 patients, 11 patients had ultrafiltration failure (NUF <400 mL after 4 hours). For these patients the contribution of free water to $TCUF_{0\text{-}1}$ was significantly lower than for those with normal ultrafiltration (20% vs. 48%, $P < 0.05$). A strong correlation was present between free water transport as a percentage of total fluid transport and the maximum dip in D/P sodium ($r = 0.84$). The correlation was not significant with the difference in net ultrafiltration of 3.86% and 1.36% solutions ($r = 0.24$, $P = 0.3$).

Conclusion. The method applied here is the first direct quantification of free water transport, calculated from a single standard peritoneal function test. It offers a quick possibility to evaluate patients suffering from ultrafiltration failure. In these patients free water transport was impaired, but the origin of this impairment is still to be determined.

Key words: free water transport, peritoneal dialysis, peritoneal transport, aquaporin, ultrafiltration failure, sodium sieving.

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Ultrafiltration in peritoneal dialysis (PD) is dependent on transport through the small pores and through the water channels in the endothelium of peritoneal capillaries and vessels. The anatomic equivalents of the small pores are probably the interendothelial clefts [1]. Through these pores low-molecular-weight solutes are also transported. The transendothelial water channels have been identified morphologically as aquaporin-1 by aquaporin-channel forming integral protein (CHIP) antiserum specific staining of peritoneal endothelial cells [2–4]. Aquaporin-1 is impermeable to solutes. Therefore, crystalloid osmotic-induced free water transport occurs through them. The contribution of free water transport is especially important when a hyperosmolar solution is used because the small pores are influenced by tonicity only to a limited extent. This is due to their very low reflection coefficient to glucose. In contrast, solutions with low osmolarity will induce little free water transport [5].

Several indirect methods to assess free water transport have been suggested. The difference in net ultrafiltration (NUF) between a 3.86% and a 1.36% solution is a rough indication, easy to calculate, but time consuming [6, 7]. Another way to estimate free water transport is to measure the dip in dialysate/plasma (D/P) sodium in the initial phase of a 3.86% exchange. Dilution of dialysate sodium occurs by free water transport from the circulation to the dialysate [8, 9, 10]. Inhibition of aquaporin-1 by applying $HgCl_2$ in the peritoneal cavity resulted in the absence of a dip in D/P sodium in the first hour of a hyperosmolar exchange in rats and rabbits [3, 11]. Impaired free water transport is observed frequently in patients with ultrafiltration failure, as judged from a decreased maximum dip in the D/P ratio for sodium [6, 12].

In the present study, a method was applied to quantify free water transport as a percentage of total fluid transport, using dialysate and plasma sodium concentrations during the 3.86% glucose standard peritoneal permeability analysis (SPA) [13, 14]. In this test a volume

marker (dextran 70) was added to measure fluid kinetics. In addition, multiple dialysate samples were taken during a SPA, facilitating the calculation of sodium transport at every time point. The sodium associated water transport is subtracted from the total fluid transport, resulting in the free water transport.

METHODS

Two SPAs were performed in 40 continuous ambulatory peritoneal dialysis (CAPD) patients, also described in [7]. These patients were each studied during a SPA with 1.36% glucose and one with 3.86% glucose dialysate (both PD1 Dianeal; Baxter B.V., Utrecht, The Netherlands). The interval between the two SPAs was less than one month.

Patients

The patients had a mean age of 50 years (range 22 to 74 years). The duration of CAPD therapy ranged from 2 to 45 months, mean 9 months. All patients used commercially available dialysate (Baxter B.V.). None of the patients had peritonitis during the study period or in the preceding four weeks.

Procedure

The SPAs were performed during four-hour dwell periods, as described previously [13]. Dialysate samples were taken before instillation and at multiple time points during the test (10, 20, 30, 60, 120, 180, and 240 min). Blood samples were taken at the beginning and at the end of the test period. A volume marker, dextran 70 1 g/L (Hyskon, Medisan Pharmaceuticals AB, Uppsala, Sweden), was used to calculate fluid kinetics. To prevent a possible anaphylactic reaction to dextran 70, dextran 1 (Promiten, NPBI, Emmercompascuum, The Netherlands) was injected intravenously before instillation of the test bag [15].

Measurements

Total dextran was determined by means of high performance liquid chromatography (HPLC) [16]. Creatinine, urea, and urate were measured by enzymatic methods (Boehringer Mannheim, Mannheim, Germany). All electrolytes were determined using ion selective electrodes. Glucose was measured by the glucose oxidase-peroxidase method, using an autoanalyzer (SMA-II, Technicon, Terrytown, NJ, USA).

Calculations

All calculations were performed as previously described by Pannekeet et al [13]. Briefly, the changes in intraperitoneal volume are the result of transcapillary ultrafiltration and fluid absorption (including absorption to the lymphatics and disappearance to the interstitial tissues). Both parameters were assessed with the intraperitoneally administered volume marker dextran 70. Transcapillary ultrafiltration (TCUF) was calculated from the dilution of the volume marker, by subtracting the initial intraperitoneal volume (IPV) from the theoretical IPV (when both fluid absorption and sampling would not have been present) at any time point. Because transcapillary ultrafiltration has its maximum value during the initial phase of a dwell, transcapillary ultrafiltration rate in the first minute ($TCUF_{0\text{-}1}$) was calculated, using the Lineweaver-Burke plot, that is, the linear regression between the reciprocal values of the transcapillary ultrafiltration obtained during the SPA and the reciprocal of time [17]. The net ultrafiltration is the difference between the transcapillary ultrafiltration and the effective fluid absorption.

Peritoneal handling of low molecular weight solutes was expressed as mass transfer area coefficient (MTAC) and D/P ratios. The MTAC represents the maximal theoretical diffusive clearance of a solute at $t = 0$, before transport has actually started. In this study we used the Waniewski model, where the solute concentration was expressed per volume of plasma water [18, 19].

Calculations of free water transport using dialysate and plasma sodium were performed on the 3.86% glucose SPAs. Applying the same method on the 1.36% glucose SPAs provided reliable values for transport through the small pores in the first hour of the exchange, but the Lineweaver-Burke plots showed unacceptable low regression coefficients. Therefore, they could not be used to calculate $TCUF_{0\text{-}1}$. D/P sodium was calculated as the dialysate sodium concentration divided by the plasma sodium concentration. Maximum dip in D/P sodium was the difference between the initial D/P sodium and the lowest D/P sodium (usually after 1 to 2 hours). Correction for Na^+ diffusion from the circulation to the dialysate, known to cause blunting of the decrease in D/P Na^+, was done as previously described [20], using the mass transfer area coefficient of urate. Because of the change of MTACs of small solutes during a dwell, the MTAC of urate was calculated at different time points during the dwell. The calculated sodium concentration in the dialysate due to diffusion can then be subtracted from the measured concentration at any time point, resulting in the actual Na^+ sieving. Using the three-pore model, the part of the osmotically induced fluid flow passing through the small pores will be carrying sodium without any sieving (sieving coefficient is 1). The rest of the fluid flow will pass the ultra small pores (aquaporins) with complete sieving of sodium (sieving coefficient is 0). This means that the net sieving coefficient is the fraction that passes through the small pores, and that 1 minus the net sieving coefficient

is the fraction that passes through the ultra small pores [21].

Transport through the small pores was calculated by multiplying the sum of the initial intraperitoneal volume and the ultrafiltered volume (in L) with the dialysate sodium concentration after correction for diffusion:

$$\begin{aligned}&\text{amount sodium present}\\&\quad=(\text{initial IPV}+\text{ultrafiltered volume})\\&\times\ \text{dialysate sodium}\\&\qquad(\text{after correction})\end{aligned}$$

This can be calculated for time point zero (t_0) and for any time point during the dwell (t_t). Subtracting t_0 from t_t results in the amount of sodium transported of any time point of the dwell: dividing the amount of transported sodium with the sodium concentration in the small pores (which is the average of the plasma sodium concentration and the dialysate sodium concentration) results in the volume (in L) of fluid transported through the small pores:

$$\begin{aligned}&\text{fluid transport through small pores}\\&\quad=\frac{\text{amount of sodium transported}}{\text{sodium concentration in the small pores}}\end{aligned}$$

The volume transported through the small pores was then subtracted from the total volume transported, resulting in free water transport. The contribution of this free water transport to the total fluid transport was expressed as a percentage:

$$\begin{aligned}&\%\ \text{free water transport}\\&\quad=\frac{\text{volume free water transport}}{\text{total fluid transport}}\times 100\%\end{aligned}$$

With the calculation of the transcapillary ultrafiltration through the small pores for each time point during the SPA, a Lineweaver-Burke plot was made to calculate small pore transport in the first minute ($SP_{0\text{-}1}$). This method showed good regression coefficients (median $r = 0.98$, range 0.95 to 0.99). Subtracting the obtained value from the $TCUF_{0\text{-}1}$ resulted in free water transport in the first minute. The contribution of free water transport to total transcapillary ultrafiltration was examined during the first minute of the 3.86% glucose dwell and after 60 minutes.

Statistical analysis

Results are presented as median values and ranges. For the comparison of the results of the two solutions, the paired Student *t* test was employed for comparisons within one patient. Spearman rank correlation analysis was used to investigate possible relationships. For comparison of the groups with and without ultrafiltration failure the Mann-Whitney *U* test was applied. A Bland-Altman plot was made to compare the method with and without correction for sodium diffusion [22].

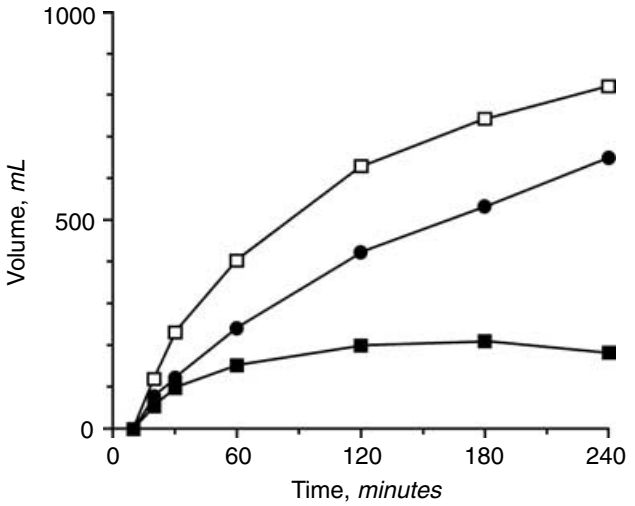

Fig. 1. Fluid profile for all 40 patients. Total transcapillary ultrafiltration during the 4-hour dwell (□), transport through the small pores (●), and free water transport (■).

RESULTS

From the 40 patients, 11 patients had ultrafiltration failure (NUF <400 mL after 4 hours). The patients with normal ultrafiltration were somewhat older than those with ultrafiltration failure (52 vs. 29 years, NS) and were treated for a shorter period of time, 8 months (2 to 36) versus 20 months (2 to 45), $P < 0.05$.

For the 1.36% glucose dwell, total fluid transport in the first hour was 164 mL (32 to 399) for the whole group. Transport through the small pores was 129 mL (14 to 399), and free water transport was 35 mL (0 to 150). When the contribution of free water transport was calculated for the first hour of a 1.36% glucose dwell, a value of 23% (0 to 91%) for the patients with normal ultrafiltration was found versus 3% (0 to 21%) for patients with ultrafiltration failure ($P < 0.05$).

Using the 3.86% glucose solution, the total fluid transport in the first hour was 404 mL (70 to 726) for the whole group. Transport through the small pores was 269 mL (56 to 526), and free water transport was 135 mL (13 to 290). The fluid profile for the 3.86% glucose dwell for all 40 patients is given in Figure 1. The parameters for fluid kinetics in patients with and without ultrafiltration failure are listed In Table 1. For the patients with ultrafiltration failure free water transport was significantly lower in the first hour (72 vs. 164 mL, $P < 0.05$) and in the first minute (2.0 vs. 7.1 mL, $P < 0.05$) of a dwell, compared to patients without UF failure. Figure 2 shows the four-hour fluid profiles for the patients with normal UF and for patients with UF failure. The lines for total transcapillary

Table 1. Parameters for fluid kinetics for 40 patients using an exchange with a 3.86% glucose solution

	Normal UF ($N = 29$)	UF failure ($N = 11$)
First hour		
TCUF *mL*	463 (260–726)	267 (70–571)
Small pore transport *mL*	299 (131–526)	195 (56–395)
Free water transport *mL*	164 (13–290)	72 (14–176)[a]
% Free water transport	35 (15–62)	26 (14–44)[a]
First minute		
$TCUF_{0\text{-}1}$ *mL*	14.8 (4.2–38.1)	7.4 (1.6–23.2)
Small pore $transport_{0\text{-}1}$ *mL*	7.9 (2.5–24.4)	5.0 (1.3–11.8)
Free $water\ transport_{0\text{-}1}$ *mL*	7.1 (1.2–19.8)	2.0 (0.0–11.4)[a]
% Free $water\ transport_{0\text{-}1}$	48 (16–78)	20 (0–49)[a]

The group is divided in patients with normal ultrafiltration and patients with ultrafiltration failure.
[a] $P < 0.05$.

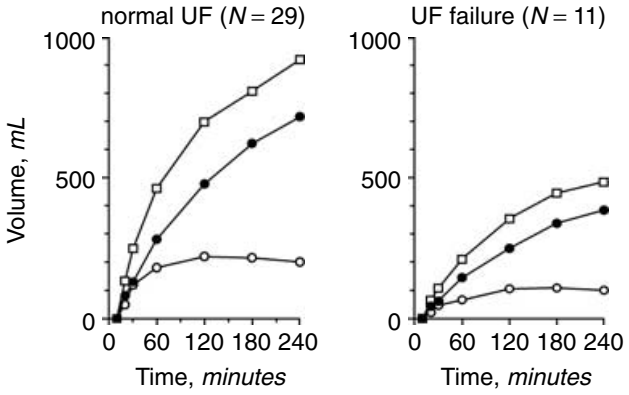

Fig. 2. Fluid profiles for the patients with normal ultrafiltration (left) and with ultrafiltration failure (right). Total transcapillary ultrafiltration during the 4-hour dwell (□), transport through the small pores (•) and free water transport (○).

Table 2. Results of the 3 different methods to assess free water transport in 40 patients

	Normal UF ($N = 29$)	Ultrafiltration failure ($N = 11$)
% Free $water\ transport_{0\text{-}1}$	48 (16–78)	20 (0–49)[a]
Maximum dip D/P sodium	0.083 (0.030–0.120)	0.031 (0.011–0.089)[a]
Difference in net $UF_{3.86\%-1.36\%}$ *mL*	710 (396–1320)	306 (127–687)[a]

% Free $water\ transport_{0\text{-}1}$ is the percentage of free water transport contributing to the total transcapillary fluid transport during the first minute of a 3.86% glucose dwell.
[a] $P < 0.05$.

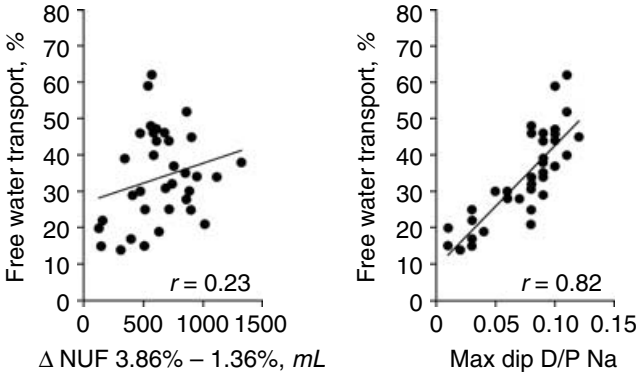

Fig. 3. Correlation between the different methods to assess free water transport. The correlation between free water transport as a percentage of the total fluid transport in the first hour and the difference in net ultrafiltration between a 3.86% and a 1.36% glucose exchange (left). The correlation between free water transport as a percentage of the total fluid transport in the first hour and the maximum dip in D/P sodium using a 3.86% glucose solution (right).

ultrafiltration and fluid transport through the small pores approach each other in the right panel (Fig. 2), due to impaired free water transport. Table 2 shows the results for the different methods to assess free water transport. The contribution of free water transport to total transcapillary ultrafiltration in the first minute was 48%. For patients with UFF this was significantly lower: 20% ($P < 0.05$). In addition, the maximum dip in D/P sodium was significantly lower in patients with ultrafiltration failure, as well as the difference between the 3.86% glucose exchange and the one with 1.36% glucose. Figure 3 shows the strong correlation between free water transport calculated as a percentage of total fluid transport and the maximum dip in D/P sodium (Fig. 3, right panel). No significant correlation was present with the difference in net ultrafiltration between 3.86% and 1.36% solutions ($r = 0.23$, $P = 0.3$), as shown in the left panel of Figure 3. The correlation between the percentage of free water transport at 60 minutes, using the diffusion corrected method and the fast-fast peritoneal equilibration test (PET) without correction for sodium diffusion was reasonably good with a correlation coefficient of 0.84, $P < 0.01$. A Bland-Altman plot in Figure 4 shows the means and the differences for both methods; an underestimation of about 10% in the contribution of free water transport is made when no correction for diffusion is performed.

DISCUSSION

In the present study, a method was applied to calculate the volume of free water transport using the removal of sodium in the first phase of the dwell. Comparisons were made with the currently available methods to estimate free water transport. The method used in this study is an extension of the method described by La Milia et al, who performed a 1-hour PET test and calculated ultrafiltration through the ultra small pores by subtracting the amount of fluid transporting sodium through the small pores from the total ultrafiltered volume [abstract; La Milia et al, *Nephrol Dial Transplant* 17(Suppl 3):17–18, 2002]. The addition of dextran 70 to the test fluid and the dialysate sampling at multiple time points enabled us to expand the calculations because intraperitoneal volume and dialysate sodium were available for every time point.

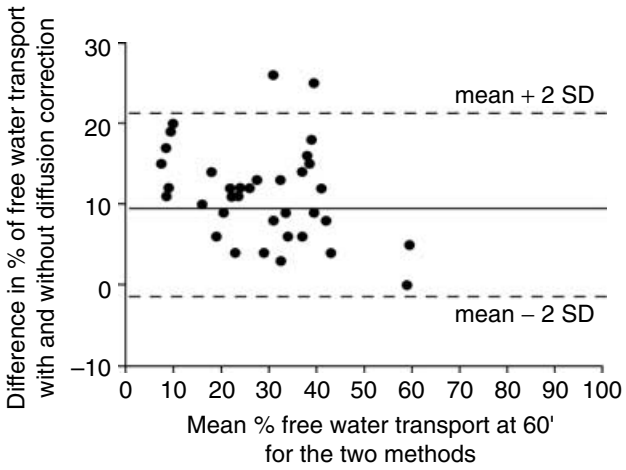

Fig. 4. Bland and Altman plot of the differences between the calculations of free water transport in the first hour of a dwell versus their means. An underestimation of free water transport of about 10% was present when no correction for sodium diffusion is made. No systematic errors were found.

In this way it was possible to make fluid profiles and perform Lineweaver-Burke plots to calculate $TCUF_{0\text{-}1}$ and $SP_{0\text{-}1}$. The values of free water transport in the first hour of the test, as reported in this study, showed a reasonably good correlation with the values calculated using the fast-fast PET of La Milia et al, in which no correction for sodium diffusion was performed. However, an underestimation of about 10% was observed. This implies that the fast-fast PET only gives accurate information on free water transport when a correction for sodium diffusion is made. This can easily be done with the MTAC of creatinine, as described by Westra et al [23].

It appeared that free water transport in the first minute contributed 48% to the total fluid removal when patients did not suffer from ultrafiltration failure. Previously reported values for free water transport were also found to average 50%. However, these values were assessed either by indirect methods [24, 25], or with computer simulations [26, 27]. The patients with ultrafiltration failure had significantly lower free water transport compared to the patients with normal UF. Loss of sodium sieving has been described previously in patients with impaired ultrafiltration [6, 28], but it was never quantified and related to the total fluid removal. The reason for this impaired free water transport can theoretically be attributed to loss of aquaporin-1 in peritoneal endothelia. However, Goffin et al examined the peritoneum of a patient with loss of transcellular water transport and found normal expression of aquaporin-1 [29]. Therefore, it seems more likely that a functional alteration is present, rather than an anatomic alteration. The causes for this functional impairment are not known. The enduring exposure to unphysiologic dialysis fluids could have led to glycation of aquaporins. Alternative explanations could be that oxidative stress leads to oxidant mediated protein damage and function alteration, or that nitrosylation of aquaporins occurs, resulting in altered function. Alterations in the interstitial tissues can also be postulated, but the mechanism of selective hampering of aquaporin-1 function is difficult to comprehend.

The correlation between the different methods to assess peritoneal free water transport in the 40 patients investigated in this study suggests that all three methods measure the same phenomenon. Previous investigations already showed a reasonably good relationship between the dip in D/P sodium and the difference in net ultrafiltration between a 3.86% glucose dwell and a 1.36% dwell [7]. In the present study, an even better correlation was found between the maximum dip in D/P sodium and the percentage free water transport in the first hour compared to the total fluid removal.

In the methodology of the present study, a correction for sodium diffusion was performed using the MTAC of urate, which was found to be similar to the MTAC of sodium in studies by Imholz [30] and Leypoldt [31]. Others have reported a somewhat lower MTAC for sodium [19, 21, 32]. This difference can be explained by the ultra-low sodium dialysate that was used in the studies of Imholz and Leypoldt (102 mmol/L), whereas the others used normal sodium containing dialysate. It seems unlikely that the increase in concentration gradient would have had an important influence on the MTAC of sodium in the first studies. To calculate an MTAC (which reflects diffusive transport), one needs a concentration gradient between dialysate and plasma. In case of a low concentration gradient (as is present in the normal sodium dialysate studies) small inaccuracies in the determinations, and interference with convective transport, may influence the calculated MTAC values. This can be illustrated by the very large standard deviations in some of these studies [32]. This is not the case when a large concentration difference is present. A dependency of the MTAC of a solute on the concentration gradient has never been shown for urea, creatinine, uric acid, inulin, and serum proteins. Also, for the diffusive transport of glucose, no differences were observed, when the glucose absorption after a four-hour dwell with glucose 1.36% dialysis solution was compared to a dwell with glucose 3.86% [7]. Although nonelectrolytes have no dependency of the MTAC on the concentration gradient, this could be the case for an ion-like sodium. However, in study in rats by Cheng et al [33], no significant differences between diffusive mass transport coefficients of sodium calculated using a dialysate containing 0.9% NaCl (153 mmol/L) and 0.6% NaCl (102 mmol/L) were observed. Because the commercially available dialysis solutions contain 132 mmol/L, no difference is to be expected between this solution and the ultra-low sodium (102 mmol/L) solution used by Imholz et al. Consequently, the method of correcting for sodium

diffusion by using the MTAC of urate as applied here seems appropriate.

CONCLUSION

The method applied here is the first direct quantification of free water transport, calculated from a single standard peritoneal function test. It facilitates measuring free water transport in patients. The good correlation with the fast-fast PET of La Milia offers a quick possibility to evaluate patients suffering from ultrafiltration failure when a correction for sodium diffusion is made.

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