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Mini-peritoneal equilibration test: A simple and fast method to assess free water and small solute transport across the peritoneal membrane

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Mini-peritoneal equilibration test: A simple and fast method to assess free water and small solute transport across the peritoneal membrane.

Background. Loss of ultrafiltration (UF) of peritoneal membrane is one of the most important causes of peritoneal dialysis failure. UF is determined by osmotic forces acting mainly across small pores (UFSP) and ultrasmall pores or free water transport. At present, only semiquantitative estimates or complicated computer simulations are available to assess free water transport. The aim of this study was to assess free water transport during a 3.86% peritoneal equilibration test lasting 1 hour. In this condition, sodium transport is mainly due to convection, allowing the estimate of ultrafiltration of small pores and then of free water transport (total UF − UFSP).

Methods. In 52 peritoneal dialysis patients we performed a 3.86% peritoneal equilibration test (4 hours) and a 3.86% mini-peritoneal equilibration test (1 hour) and compared UF and small solute transports obtained with the two methods.

Results. During the 3.86% mini-peritoneal equilibration test, UFSP and free water transport were 279 ± 142 mL and 215 ± 86 mL, respectively; free water transport well correlated to total UF during the 3.86% peritoneal equilibration test ($r = 0.67$). The groups of peritoneal transporters, categorized according to glucose dialysate ratio (D/D_0) and to creatinine/plasma ratio (D/P_{Creat}), were in good agreement for the two peritoneal equilibration tests (weighted κ 0.62 and 0.61, respectively).

Conclusion. The 3.86% mini-peritoneal equilibration test is a simple and fast method to assess free water transport. It also gives information about total UF and small solute transports and it is in good agreement with the 3.86% peritoneal equilibration test.

Loss of ultrafiltration (UF) of peritoneal membrane is one of the most important causes of peritoneal dialysis failure [1–3]. According to the three-pore model [4–6], the transperitoneal solute and water transfer is determined by various hydraulic and osmotic forces acting across three types of "pores" in the capillary walls: aquaporin-1, which has also been defined as ultrasmall pores, small pores, and large pores. During a hypertonic dwell, approximately 60% of total UF is dependent on transport through small pores (UFSP), which is coupled to the transport of small solutes, whereas nearly 40% of UF occurs through ultrasmall pores, a transcellular transport of free water without solutes [4, 7, 8].

The free water transport is responsible of sodium sieving (i.e., the dip in dialysate sodium concentration in the initial phase of a 3.86% glucose peritoneal equilibration test) because of the dilution of dialysate sodium by free water transport from the circulation to the dialysate [4, 7, 8]; its reduction may contribute to UF failure [9, 10]. For this reason, a reliable tool to assess the free water transport is of great clinical importance.

Several indirect methods to assess free water transport have been suggested.

The 3.86% peritoneal equilibration test provides better information on UF than the standard 2.27% peritoneal equilibration test [11] because the larger drained volume reduces the likelihood of measurement errors. In addition, the 3.86% peritoneal equilibration test, by the dialysate/plasma sodium concentration ratio (D/P_{Na}) or by the magnitude of the dip in D/P_{Na}, gives a semiquantitative assessment of free water transport [12]. However, even after correction for sodium diffusion [13], D/P_{Na} and the dip in D/P_{Na} are only approximate estimates of free water transport.

Another indirect method to estimate free water transport is the comparison of net UF obtained during two modified peritoneal equilibration test (standard peritoneal permeability analysis) performed with a peritoneal dialysis solution with a glucose concentration of 1.36% or of 3.86% [14], but this method is complicated, time-consuming, and not easy applicable in everyday clinical

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practice. In addition, it can not properly quantify free water transport, because the difference in net UF during a 1.36%/3.86% test is the sum of the contribution of free water transport and of UFSP during the 3.86% test.

Altogether, at present free water transport can be estimated only through complicated computer simulations [5].

With the aim of assessing free water transport, we started from the consideration that during the first hour of a 3.86% exchange the free water transport is maximal, as glucose in the dialysate is at its highest concentration, and that diffusive sodium transport is very low, because of a low plasma to dialysate sodium gradient, and shortened the duration of the 3.86% peritoneal equilibration test from 4 hours to 1 hour (3.86% mini-peritoneal equilibration test). In this condition, UF through the large pores and the lymphatic transport is very low [15] and the total sodium transport is mainly due to convective transport through small pores. It would then be possible to estimate UFSP as the sodium removal divided by the plasma water sodium concentration; free water transport could be easily calculated subtracting UFSP from total UF.

The second aim of our study was to compare UF and small solute transport obtained during the 3.86% mini-peritoneal equilibration test (1 hour long) with those of the 3.86% peritoneal equilibration test (4 hours long).

METHODS

Patients

After having given their informed consent, 52 peritoneal dialysis patients (22 males and 30 females with a mean age of 58 ± 14 years) attending at Manzoni Hospital, Lecco, between September 2000 and September 2004 were enrolled in the study and underwent a 3.86% peritoneal equilibration test (4 hours long), followed after 48 hours by a 3.86% mini-peritoneal equilibration test (1 hour long). All patients used commercially available peritoneal dialysis solutions. The median time on peritoneal dialysis was 4 months (range 2 to 136 months). Their medical condition was stable and at the time of test they had been free of peritonitis for at least 4 weeks. Six patients had clinical signs of overhydration (edema).

Procedure

We used a modified peritoneal equilibration test, which differed from the classic method [11] insofar as the peritoneal dialysis solution contained a 3.86% instead of 2.27% concentration of anhydrous glucose. This procedure has been described in details elsewhere [16]. In particular, lactate (35 mEq/L) was used as the buffer, with a nominal pH of 5.0 to 6.5 and a nominal sodium concentration of 132 to 134 mmol/L. Blood samples were taken at the start of the test (P_0'), after 60 minutes (P_{60}'), and at the end of the test, 240 minutes (P_{240}'). The overnight dialysate (D_{Night}) samples were taken from the bag; the fresh peritoneal dialysis fluid (D_0') samples were taken from the bag at the end of the infusion. After the complete infusion of 2 L of peritoneal dialysis solution, and after having flushed back 30 mL of dialysate, 20 mL dialysate samples were taken after 1, 60, and 240 minutes (D_1', D_{60}', and D_{240}'). After 240 minutes, the dialysate was gravity collected for at least 20 minutes.

The 3.86% mini-peritoneal equilibration test was performed after 48 hours from the 3.86% peritoneal equilibration test using the same solutions and modalities; the only difference was the duration of the exchange that was shortened to one hour. Blood samples were taken at the start of the test and 20 mL dialysate samples were taken after 1 and 60 minutes (D_1' and D_{60}').

Analytic methods

Plasma and dialysate creatinine, total protein, and glucose concentrations were analyzed using a Hitachi 717 (Hitachi, Ltd., Tokyo, Japan); an enzymatic method was used to analyze creatinine, in order to eliminate the effect of the high dialysate glucose concentration on the measurement of creatinine concentrations in the dialysate. The total sodium concentrations in the plasma, fresh peritoneal dialysis solution, and dialysate were analyzed twice using an IL943 flame photometer (Instrumentation Laboratory, Milan, Italy); the ionized sodium concentrations in the plasma, fresh peritoneal dialysis solution, and dialysate were analyzed using a direct ion selective electrode (Stat Profile M; Nova Biomedical Corp., Waltham, MA, USA).

Calculations

The ratio of dialysate glucose concentrations (D/D_0) was calculated dividing the dialysate glucose concentrations at the end of the peritoneal equilibration tests with that of the fresh peritoneal dialysis solution. The dialysate/plasma creatinine concentration ratio (D/P_{Creat}) was calculated at the end of the peritoneal equilibration tests; the plasma water concentration of creatinine was considered [17]. The absolute dip of dialysate sodium concentration ($DipNa_D$) during the 3.86% mini-peritoneal equilibration test was calculated as:

$$DipNa_D(mmol/L) = Na_{DialysateOut}(mmol/L) - Na_{DialysateIn}(mmol/L)$$

where DialysateIn was the fresh peritoneal dialysis solution.

The D/P_{Na} was assessed at the start ($D/P_{Na}0$) and at 60 minutes ($D/P_{Na}60$) of the peritoneal equilibration tests.

Table 1. Peritoneal transport characteristics of 52 patients in peritoneal dialysis therapy assessed during the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test

	3.86% peritoneal equilibration test	3.86% mini-peritoneal equilibration test
UF *mL*	749 ± 224 (686-749)	493 ± 170 (446-541)
UFSP *mL*	—	279 ± 142 (239-318)
Free water transport *mL*	—	215 ± 86 (191-239)
D/D_0	0.28 ± 0.08 (0.25-0.30)	0.58 ± 0.09 (0.56-0.61)
D/P_{Creat}	0.69 ± 0.10 (0.66-0.72)	0.43 ± 0.09 (0.41-0.46)
Na_P *mmol/L*	141.8 ± 2.1 (141.2-142.4)	142.2 ± 2.7 (141.5-143.0)
$Na_{DialysateIn}$ *mmol/L*	133.4 (132.2-134.7)	133.2 (132.2-134.8)
$Na_{DialysateOut}$ *mmol/L*	127.5 ± 5.2 (126.1-129.0)	123.3 ± 3.9 (122.2-124.4)
$DipNa_D$ *mmol/L*	−6.2 ± 5.1 (−7.6, −4.7)	−10.0 ± 4.2 (−11.1, −8.8)
$D/P_{Na}60'$	0.89 ± 0.03 (0.88-0.90)	0.89 ± 0.03 (0.88-0.89)
NaR *mmol*	82 ± 26 (75-89)	40 ± 20 (34-45)

Abbreviations are: UF, ultrafiltration rate at end of tests; UFSP, ultrafiltration across small pores; D/D_0, ratio of dialysate glucose concentrations at end and at start of tests; Na_P, plasma sodium concentration; $Na_{DialysateIn}$, sodium concentration at the start of the test in the fresh peritoneal diaysis solution; $Na_{DialysateOut}$, dialysate sodium concentration at the end of the test; D/P, dialysate-to-plasma ratio; $DipNa_D$, difference of dialysate sodium concentration at end and at start of test; NaR, sodium removal during the tests.

Data are expressed as mean ± 1 SD and 95% confidence interval or as median values and interquartile ranges in the brackets.

The dip of D/P_{Na}, during the 3.86% mini-peritoneal equilibration test, was calculated as:

$$DipD/P_{Na} = D/P_{Na}60 - D/P_{Na}0$$

During the 3.86% mini-peritoneal equilibration test, the free water transport was calculated as follows:

$$\text{Free water transport (mL)} = \text{Total UF (mL)} - \text{UFSP (mL)}$$

During the 3.86% mini-peritoneal equilibration test, UFSP was calculated as follows:

$$UFSP\ (mL) = [NaR(mmol) \bullet 1000]/Na_p$$

where NaR (mmol) was sodium removal, calculated as:

$$[Volume_{DialysateOut}\ (L) \bullet Na_{DialysateOut}(mmol/L)] - [Volume_{DialysateIn}(L) \bullet Na_{DialysateIn}(mmol/L)]$$

and Na_p was the ionized sodium plasma water concentration assessed by direct ion selective electrode (see the **Appendix** for detailed description of performed calculations).

Statistical analysis

The data with normal distribution were expressed as mean values ± 1 standard deviation (SD), together with their 95% confidence intervals (95% CI). Median values and interquartile ranges were given for asymmetrically distributed data.

According to the mean values ± 1 SD of D/D_0 and D/P_{Creat} [11], the patients were categorized as high (H), average (A), and low (L) peritoneal transporters. The agreement of nominal classification of peritoneal transport categories, assessed by the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test, was determined by the weighted kappa statistics (κ) [18] together with its 95% CI. Kappa values > 0.80, 0.61 to 0.80, and 0.41 to 0.60 were considered to reflect very good, good, and moderate agreement, respectively [18].

Pearson correlation analysis was used to investigate possible relationships between free water transport, total UF, $DipNa_D$, D/P_{Na}, and between the values of D/P_{Creat} during the 3.86% peritoneal equilibration test and those during the 3.86% mini-peritoneal equilibration test.

A P value of <0.05 was considered significant. All of the statistical analyses were made using SPSS for Windows statistical software (release 11.0).

RESULTS

Table 1 summarizes the peritoneal transport characteristics during the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test, which were expressed as UF, UFSP, free water transport, D/D_0, D/P_{Creat}, Na_P, Na_D, $DipNa_D$, D/P_{Na} and NaR. We were able to calculate the total D/D_0 in 51 instead of 52 patients, since one glucose dialysate concentration was missing in one patient during the 3.86% peritoneal equilibration test. Among the 52 patients, four of the six patients who had overhydration also had UF failure (total UF <400 mL after 4 hours of 3.86% peritoneal equilibration test).

According to the method we proposed, starting from NaR, Na_P, and total UF during the 3.86% mini-peritoneal equilibration test, we calculated the mean UFSP and free water transport, which were 279 ± 142 mL (95% CI 239-318 mL) and 215 ± 86 mL (95% CI 191-239 mL), respectively.

At the end of the 3.86% mini-peritoneal equilibration test, the mean free water transport was 46 ± 18% of total UF and correlated well with total UF after the 3.86% peritoneal equilibration test ($r = 0.67$). This was not the case for D/P_{Na} at 60 minutes that was poorly correlated to total UF during both the 3.86% peritoneal equilibration

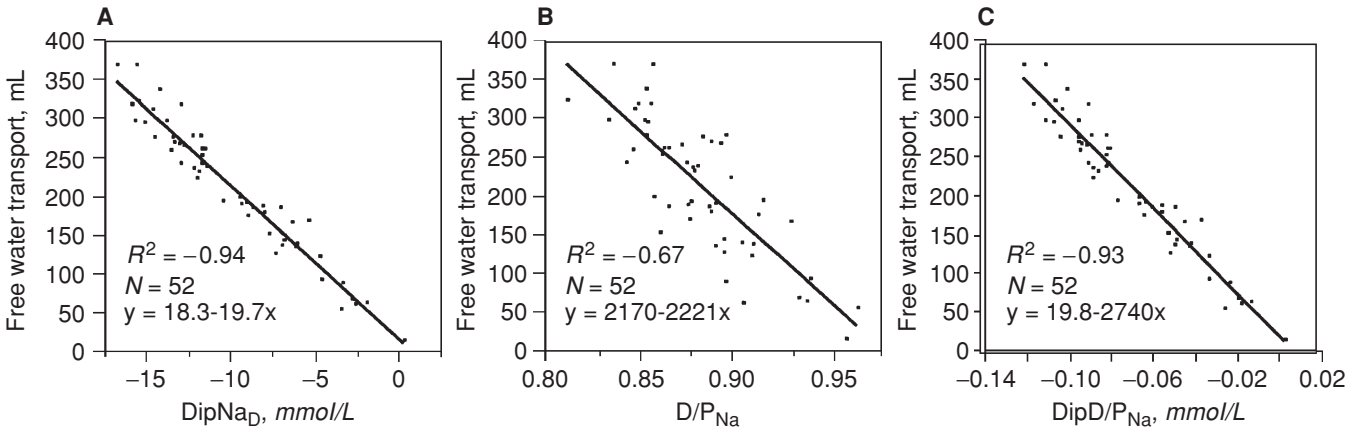

Fig. 1. The linear correlations of absolute $DipNa_D$ (*A*), D/P_{Na} (*B*), and $DipD/P_{Na}$ (*C*) with free water transport during the 3.86% mini-peritoneal equilibration test. Abbreviations are: $DipNa_D$, difference of sodium concentration between the dialysate at the end of the test and the fresh peritoneal dialysis fluid at the start of the test; D/P_{Na}, dialysate-to-plasma ratio of sodium at end of test; $DipD/P_{Na}$, difference of D/P_{Na} between the end and start of test.

Table 2. Comparison of peritoneal transport groups categorized according to D/D_0 glucose during the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test

3.86% mini-peritoneal equilibration test	3.86% peritoneal equilibration test			
	High	Average	Low	Total
High	5	2	0	7
Average	3	31	2	36
Low	0	2	6	8
Total	8	35	8	51

D/D_0 is the ratio of dialysate glucose concentrations at end and at start of tests. The level of agreement was good (weighted κ 0.62 and 95% CI 0.40-0.84).

Table 3. Comparison of peritoneal transport groups categorized according to D/P_{Creat} during the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test

3.86% mini-peritoneal equilibration test	3.86% peritoneal equilibration test			
	High	Average	Low	Total
High	4	3	0	7
Average	2	33	2	37
Low	0	2	6	8
Total	6	38	8	52

D/P_{Creat} is dialysate-to-plasma ratio of creatinine. The level of agreement was good (weighted κ 0.61 and 95% CI 0.38-0.84).

test ($r = -0.37$) and the 3.86% mini-peritoneal equilibration test ($r = -0.37$).

Figure 1 shows linear correlations of $DipNa_D$, $DipD/P_{Na}$, and D/P_{Na} with free water transport. Even if $DipNa_D$, $DipD/P_{Na}$, and D/P_{Na} are partially mathematical coupled with UFUSP, they clearly indicate that absolute $DipNa_D$ and $DipD/P_{Na}$ are better predictors of free water transport than D/P_{Na} (R^2 of −0.94, −0.93, and −0.67, respectively).

In Tables 2 and 3 we reported the patient distribution in groups of peritoneal transporters (low, average, and high) categorized according to values of D/D_0 and D/P_{Creat} (as reported in Table 1) during the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test. Only slight changes in category occurred for a few patients. The diagonals of the two tables express the degree of exact agreement between the categories of peritoneal transporters obtained during the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test. This was 82% for D/D_0 (i.e., 42/51) and 83% for D/P_{Creat} (i.e., 43/52), respectively. The weighted κ values (chance-corrected proportional agreement) indicated a good agreement between the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test for both D/D_0 and D/P_{Creat} [weighted κ value of 0.62 (95% CI 0.40-0.84) and 0.61 (95% CI 0.38-0.84), respectively)].

Figure 2 shows the mean difference (Fig. 2A) and the linear correlation (Fig. 2B) between the values of D/P_{Creat} during the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test. The mean difference of D/P_{Creat} was 0.26; the values of D/P_{Creat} were well correlated.

DISCUSSION

The possibility to estimate free water transport through the peritoneal membrane could be a useful tool to assess UF failure in peritoneal dialysis patients and also to explore the complex physiology of the peritoneal membrane. However, all the previous peritoneal equilibration test (the classic and its derivations) are poorly useful to exactly quantify free water transport. Merging together the fact that during the first hour of an hypertonic dwell free water transport is maximal (since the glucose dialysate concentration is at its peak) and that the diffusive transport of sodium from blood to dialysate is very low (sodium concentration is close to its equilibrium across the peritoneal membrane and thus its gradient for diffusion is very low), in the present study we propose a

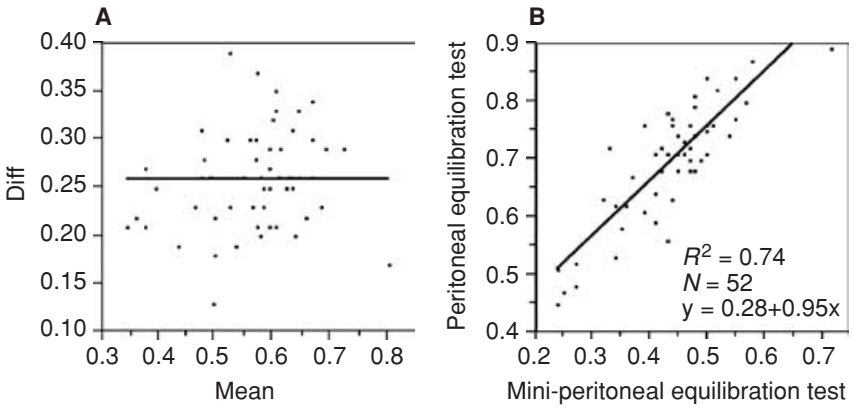

Fig. 2. Mean difference (*A*) and linear correlation (*B*) between the values of D/P_{Creat} during the 3.86%-peritoneal equilibration test and the 3.86%-mini-peritoneal equilibration test. Abbreviations are: Diff, D/P_{Creat} during the 3.86% peritoneal equilibration test minus D/P_{Creat} during the 3.86% mini- peritoneal equilibration test; mean, mean values of D/P_{Creat} during the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test.

new modified 3.86% peritoneal equilibration test, aimed at indirectly calculating free water transport by shortening the duration of the 3.86% peritoneal equilibration test from 4 hours to 1 hour (3.86% mini-peritoneal equilibration test). In these conditions near all the sodium transport is due to convection through small pores and thus the ratio of sodium removal (NaR) to plasma water sodium concentration gives the value of UF through the small pores (UFSP). It is then possible to easily calculate free water transport by subtracting UFSP from total UF.

According to our calculation, at the end of the 3.86% mini-peritoneal equilibration test, the mean free water transport represented the 46% of total UF.

We then tried to validate our method by comparing UF and small solutes transport during the 3.86% mini-peritoneal equilibration test (1 hour long) with those during the 3.86% peritoneal equilibration test (4 hours long). We found a good correlation between free water transport obtained during the 3.86% mini-peritoneal equilibration test and total UF obtained during the 3.86% peritoneal equilibration test, suggesting that the free water transport is an important fraction of total UF not only after 1 hour (3.86% mini-peritoneal equilibration test), but also after 4 hours (3.86% peritoneal equilibration test). Interestingly enough, this correlation was of greater extent than that observed between the D/P_{Na} at 60 minutes and the total UF after both the 3.86% mini-peritoneal equilibration test and the 3.86% peritoneal equilibration test, suggesting that the free water transport obtained during the 3.86% mini-peritoneal equilibration test provides more information on total UF than the D/P_{Na} at 60 minutes. This could be explained by the fact that D/P_{Na} is only a semiquantitative measure of free water transport and is also influenced by variation of plasma sodium concentrations and by the methods of plasma sodium measurement [16, 19].

Another interesting finding of this study is that the absolute $DipNa_D$ and $DipD/P_{Na}$ are better predictors of free water transport than D/P_{Na}. However, these parameters are partially mathematical coupled with free water transport because the dialysate sodium concentration, which is present in $DipNa_D$, $DipD/P_{Na}$, and in D/P_{Na}, is also used in the calculation of free water transport. In any case, it is worth noting that the absolute $DipNa_D$ provides the same information on free water transport without the need of measuring plasma Na concentrations.

We previously described the 3.86% mini-peritoneal equilibration test in a small group of peritoneal dialysis patients [abstract; La Milia et al, *Nephrol Dial Transplant* 17(Suppl 3):17–18, 2002]; the present study is the validation of the test in a larger group of peritoneal dialysis patients.

After its first description, our method has been validated by computer simulation [20].

One possible criticism to our method is that it could overestimate UFSP, since we did not correct the calculation for the small amount of sodium diffusion occurring during the test and we did not consider the UF through the large pores and the negative lymphatic absorption in the calculations. However, according to Venturoli and Rippe [20], this overestimation of UFSP was very low from the clinical point of view (nearly 3%); the cumulative UF we omitted (i.e., UF through the large pores minus UF through the lymphatic system) was only of 15 mL after a dwell of 1 hour. According to other studies [21, 22], the mass area transfer coefficient (MTAC) during a 3.86% peritoneal equilibration test could be lower than the value of 6 mL/min used by Venturoli and Rippe [20] to correct UFSP for sodium diffusion: in this case, the overestimation of our method would be even less important. In any case, it is possible to adjust the free water transport for sodium diffusion as suggested by Venturoli and Rippe [20] [free water transport = total UF + 15 – (0.92 • UFSP).

With the aim of extending the calculation of free water transport to a dwell lasting 4 hours, an extension of our method was applied to a 3.86% peritoneal equilibration test performed with the addition of a volume marker (dextran 70) in the peritoneal cavity (3.86% glucose standard peritoneal permeability analysis) [23]. Even if

sodium diffusion through small pores was taken into account, the method proposed by Smit et al [23] is too elaborated and complicated to allow its use in everyday clinical practice. Indeed, it requires multiple dialysate samples, the volume marker must be determined by a sophisticated methodology [high-performance liquid chromatography (HPLC)], and complex calculations are needed. Interestingly enough, Smit et al [23] found a reasonably good correlation between the values of free water transport in the first hour of their test and those calculated with our method, even if we did not perform any correction for sodium diffusion. According to their findings, our method would underestimate free water transport of about 10%. However, in the study by Smit et al, the mean absolute values of this underestimate were only of 16 mL in the patients with normal UF and of only 7 mL in the patients with UF failure.

Finally, we categorized the patients as high, average, and low peritoneal transporters on the basis of the values of D/D_0 and D/P_{Creat} [11] obtained during the 3.86% peritoneal equilibration test and the 3.86% mini peritoneal equilibration test. We found a good agreement of categorization of peritoneal transporters between the two peritoneal equilibration tests for both the two parameters. Moreover, the observed few disagreements were never of more than one category of peritoneal transporters. Also, the values of $D/P_{Creat,}$ obtained during the 3.86% peritoneal equilibration test and the 3.86% mini-peritoneal equilibration test were well correlated. This indicates that the 3.86% mini-peritoneal equilibration test would be able to give similar information than the 3.86% peritoneal equilibration test, but in a simpler and shorter way.

Moreover, the exact quantification of free water transport provided by our method can give additional information in patients with UF failure. For instance, in the six patients with clinical signs of overhydration, we calculated with our method a free water transport of less than 100 mL (that is 4% to 26% of total UF), but only in four of them an UF failure was identified on the basis of the classic parameter (i.e., a total UF <400 mL during a 3.86% peritoneal equilibration test).This is of particular importance from the clinical point of view, considering that in this subset of patients having an impairment of aquaporin-1 channels, hypertonic glucose solutions are not useful, and alternative ones, such as icodextrin, should be considered instead.

CONCLUSION

The 3.86% mini-peritoneal equilibration test is a new, simple, and fast method to assess transcellular free water transport without the need of complicated corrections for sodium diffusion. Moreover, the 3.86% mini-peritoneal equilibration test, which is less time consuming and more practical, gives information on total UF and small solute transport in good agreement to the 3.86% peritoneal equilibration test, lasting 4 hours. For these reasons, the 3.86% mini-peritoneal equilibration test could become a useful tool for periodical clinical evaluation of peritoneal dialysis patients in everyday clinical practice. Further studies evaluating normal values of the different transport and net UF parameters obtained with this method are awaited.

APPENDIX

The transport of solutes during peritoneal dialysis is mediated by diffusion and convection [24]. According with the first law of diffusion proposed by Fick, the rate of instantaneous diffusive solute transfer (J_sDiff) can be calculated as follows:

$$J_s\text{Diff} = (D_f/\Delta_x) \cdot A\Delta C \qquad \text{(equation 1)}$$

where D_f is the free diffusion coefficient, Δ_x is the diffusion distance, A is the surface area and ΔC is the concentration gradient. $(D_f \bullet A)/\Delta_x$ is called the permeability surface area product or the MTAC; ΔC is the concentration difference between the plasma concentration of a solute (P) and its dialysate concentration (D).

It is possible to write the equation 1 as:

$$J_s\text{Diff} = \text{MTAC}(P - D) \qquad \text{(equation 2)}$$

When standard solutions for peritoneal dialysis are used, ΔC for Na is very low, it increases during a dwell performed with a hypertonic solution because of free water transport, and becomes maximal after 1 to 2 hours. Given the low values of MTAC and ΔC, J_sDiff for Na is very low during the first hour.

Convective transport is associated with the transport of water, occurring during ultrafiltration. It is determined by the water flux (J_v), the mean solute concentration (C_m) in the membrane and the solute reflection coefficient (σ) or Staverman coefficient. The rate of instantaneous convective solute transport (J_sConv) is expressed as:

$$J_s\text{Conv} = J_v \bullet C_m \bullet (1 - \sigma) \qquad \text{(equation 3)}$$

For reasons of simplicity C_m is often approached as:

$$C_m = (P + D)/2 \qquad \text{(equation 4)}$$

Staverman's reflection coefficient σ is the fraction of the maximal osmotic pressure that a solute can exert across a semipermeable membrane; it equals 1 for an ideal semipermeable membrane and 0 when the membrane offers no resistance to the transport of a solute. With an isoporous membrane, σ is equal to 1 minus the sieving coefficient (S), which is the ratio between the concentration of a solute in the filtrate divided by its concentration in plasma when no diffusion occurs.

The equation 3 can be rewritten as:

$$J_s\text{Conv} = J_v \bullet [(P + D)/2] \bullet [1 - (1 - S)] \qquad \text{(equation 5)}$$

Using the three-pore model [4–6], the portion of fluid flow that is osmotically induced through the small pores (UFSP) would carry sodium without any sieving ($S = 1$), whereas the portion of fluid flow through the ultrasmall pores (aquaporins) is responsible of complete sieving of sodium ($S = 0$).

During a very short dwell J_sDiff of sodium is negligible, $S = 1$, and the removal of sodium (NaR) is equal to J_sConv through the small pores. Given these considerations, J_v (or UFSP) can be expressed as:

$$J_v(\text{UFSP}) = [J_s\text{Conv(NaR)}]/[(P + D)/2] \qquad \text{(equation 6)}$$

During peritoneal dialysis performed in normal conditions, the plasma and dialysate sodium concentrations are quite close. The equation 6 can be then simplified as:

$$J_v(\text{UFSP}) = [J_s\text{Conv(NaR)}]/P \qquad \text{(equation 7)}$$

We used this simplified equation to calculate UFSP and then free water transport as follows:

$$\text{Free water transport} = \text{total UF} - \text{UFSP} \quad \text{(equation 8)}$$

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