Ionic dialysance as a method for the on-line monitoring of delivered dialysis without blood sampling

C. Manzoni, S. Di Filippo, M. Corti and F. Locatelli

Department of Nephrology and Dialysis, Lecco Hospital, Lecco, Italy

Abstract

Background. It is well known that the difference between prescribed and delivered dialysis doses greatly affects the morbidity and mortality of dialysed patients. The on-line monitoring of delivered dialysis is therefore of paramount importance. Recently, a conductivity-based method for determining Kt/V on a routine basis has been proposed.

Methods. The study was performed using a specially designed module (Biofeedback Module, COT, Hospal) which, when connected to a dialysis monitor, automatically determines effective ionic dialysance (ID). During three consecutive dialysis sessions, administered to each of eight patients at the same depurative efficiency, we determined Kt/V by using mean effective ionic dialysance and by assuming, as suggested, that urea distribution volume corresponded to 55% of body weight. This method was compared with the gold standard of the direct quantification method. The Kt/V was also calculated by using mean effective ionic dialysance and the volume of urea distribution derived from anthropometric parameters.

Results. The Kt/V determined by using mean effective ionic dialysance and by assuming that urea distribution volume corresponded to 55% of body weight was heavily underestimated (−22%). This difference was due to both the overestimate of urea distribution volume (+17%) and underestimate of effective urea clearance (KUeff) (−11%). The mean Kt/V calculated on the basis of ionic dialysance and anthropometric volume was also underestimated (−23%) since this volume was overestimated (+17%). Nevertheless, ionic dialysance and urea clearance proved to be closely correlated (r² = 0.89) so that effective urea clearance can be derived according to: KUeff = ID × 0.865 + 39.89.

Conclusions. In steady-state patients, once urea distribution volume has been correctly determined by means of direct quantification, effective urea clearance can be easily derived from ionic dialysance and Kt/V calculated on-line at each session, without blood sampling or any additional costs.

Key words: conductivity; direct quantification; effective urea clearance; Kt/V determination; ionic dialysance; urea distribution volume

Introduction

Quantification of the dialysis dose is an essential element in the management of chronic haemodialytic treatment because the adequacy of the dose has a profound effect on patient morbidity and mortality. The most useful and widely applied index to prescribe the dialysis dose (as well as to assess the dose which is actually delivered) is the Kt/V formula proposed by Sargent and Gotch [1], where K is the effective clearance of urea (commonly accepted as the marker solute for uraemic toxicity), t is the duration of the session and V is the volume of urea distribution.

Although a number of papers stress the need to define what Kt/V values are adequate (not least because of the increasing spread of high-efficiency regimens and short treatment times), the greatest problem we are facing at the moment is to check whether the prescribed dialysis dose has actually been delivered. There is often a difference, sometimes large, between the prescribed and delivered dose [2-4], which makes it essential to find a reliable, easy, non-invasive and inexpensive means of determining Kt/V during the routine monitoring of delivered dialysis.

At present, the gold standard for the determination of Kt/V is the direct quantification of removed urea, because this allows the most reliable calculation of the value of V and, consequently, the value of K. However, this method requires the total or partial collection of spent dialysate, and is thus inapplicable in everyday clinical practice. Furthermore, the recently developed on-line urea sensing devices [5,6] are still very expensive.

Blood-side Kt/V is currently determined using various kinetic models, the most widely used being the single-pool variable volume urea kinetic model (SPVV-
UKM) [7]. The Kt/V determined in this way is relatively insensitive to errors in the estimate of effective urea clearance because these lead to corresponding misestimations of volume of urea distribution, and so the ratio remains correct. However, the urea kinetic model requires the taking of blood samples before and after each treatment (if only to determine BUN values), which is why delivered dialysis is only quantified from time to time (usually monthly) and there is the obvious risk that even significant variations in the delivered dose during different sessions may go unnoticed.

Furthermore, urea transfer from one body compartment to another is not instantaneous (especially when high-efficiency regimens are used), and the disequilibrium revealed by postdialytic urea rebound [8] lasts for 30–60 min after the dialytic session. In order to avoid a significant underestimate of the volume of removed urea distribution when using the single-pool UKM, the blood sample for postdialysis BUN analysis has to be drawn when the urea rebound is exhausted: that is, almost 30 min after the end of the session. This means that the patient has to stay in the dialysis centre for longer than the duration of the dialysis session itself, which thwarts the reasons for which 'short' dialysis was born.

Two conductivity probes placed at the dialyser inlet and outlet, or a single probe alternately activated at the inlet and outlet, allow the repeated and instantaneous measurement of effective ionic dialysance [9,10] and, subsequently, the calculation of the mean effective ionic dialysance of the whole dialytic session (ID), without the need for any blood or dialysate sampling. One method for determining Kt/V on the basis of conductivity measurements has recently been suggested [11], in which effective ionic dialysance is used instead of effective urea clearance, and it is assumed that the volume of urea distribution corresponds to 55% of body weight at the end of dialysis. The possibility of using ionic dialysance seems to be of great interest because, by allowing Kt/V to be determined without the need for blood or dialysate sampling, or any other additional cost, it could make possible the on-line monitoring of delivered dialysis.

The aim of our study was to test the validity of ionic dialysance in determining Kt/V in comparison with the gold standard direct quantification method.

Subjects and methods

Eight patients undergoing regular thrice-weekly dialysis were each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency. Acetate cellulose dialysers of 2.1 m² each studied during three consecutive sessions with the same depurative efficiency.

The determination of Kt/V by means of the new method involved multiplying the volume of urea distribution determined on the basis of end of session body weight by 0.55 (V1). Ionic dialysance was measured 10 min after the start of the session and every 20 min thereafter (an average of eight determinations per session); the mean value of these measurements was used to calculate the Kt/Vid1.

As a further check, Kt/V was also calculated by using mean effective ionic dialysance and the volume of urea concentration derived from anthropometric parameters (V2) according to Watson's formula [14]: Kt/Vid2.

To verify the accuracy of the 1-min outlet dialysate flow (Qdo) and whole dialysate volume (Vd) determinations, the ratio between Qdo/min and Vd/t (where td is the session length in minutes) was calculated.

The validity of the urea distribution volume determined by direct quantification was verified by comparing it with the urea distribution volume determined by means of the equilibrated single pool variable volume (SPVV) kinetic model. Instantaneous 'diffusive' urea clearance was calculated according to equation 5 and transformed into instantaneous 'effective' urea clearance according to equation 6. The final urea distribution volume (Vtk) was calculated according to equation 7 by using the urea concentration in a blood sample drawn 30 min after the end of the session (already used to determine Vidq) as the final urea concentration. The initial urea distribution volume (Vok) was considered to be Vtk plus net ultrafiltration volume. The net urea removal obtained by means of direct quantification (equation 8) and the kinetic
model (equation 9) were compared by determining the mass balance error (MBE) according to equation 10. Only if the mass balance error did not exceed 5%, was the dialytic session considered technically satisfactory and the urea distribution volume computed as \((V_{tk} + V_{tdq})/2\).

Statistics

The values of \(Kt/V\) and urea distribution volume determined by each of the three methods, as well as those of effective mean urea clearance and mean ionic dialysance, are expressed as means ± 1 standard deviation (SD). Agreement between the estimates \(Kt/V_{id1}\), \(Kt/V_{id2}\) and \(Kt/V_{dq}\) was assessed by comparing the differences \(Kt/V_{id1} - Kt/V_{dq}\), \(Kt/V_{id2} - Kt/V_{dq}\) with the \(Kt/V_{dq}\) values (Bland–Altman analysis [15]). The mean values and SD of these differences were then calculated. Student's \(t\) test for paired data was then used to verify the difference between \(V_{1}\) and \(V_{dq}\), \(V_{2}\) and \(V_{dq}\) values and between ionic dialysance and effective urea clearance. For each patient the reproducibility of the measure of \(V_{dq}\), expressed as coefficient of variability, was also calculated. Finally, the correlation coefficient between ionic dialysance and the effective urea clearance derived by means of direct quantification was calculated.

Results

The results refer to 23 dialysis sessions because in one patient technical reasons prevented direct quantification during the third session.

The mean values of \(Kt/V\) obtained using each of the considered methods are shown in Table 1. The mean \(Kt/V\) calculated on the basis of ionic dialysance and urea distribution volume assumed to be 55% of dry weight was 22% lower than that obtained by means of direct quantification. The mean \(Kt/V\) calculated on the basis of ionic dialysance and anthropometric volume was 23% lower than that obtained by means of direct quantification.

Figure 1 shows the difference between the individual values of \(Kt/V\) obtained at each session using the conductivity method (\(Kt/V_{id1}\)) and those obtained by means of direct quantification (\(Kt/V_{dq}\), plotted against the \(Kt/V_{dq}\) values. The fact that the values

| Table 1. \(Kt/V\) calculated using the different methods |
|---------------------------------|---------------------------------|
| \(Kt/V_{dq}\) | \(Kt/V_{id1}\) | Difference (a) | \(Kt/V_{id2}\) | Difference (a) |
| Mean ± SD | Mean ± SD | Mean ± SD | % | Mean ± SD | Mean ± SD | % |
| 1.13 ± 0.19 | 0.88 ± 0.12 | -0.26 ± 0.12 | -22 | 0.87 ± 0.18 | -0.26 ± 0.09 | -23 |

\(Kt/V_{dq}\), \(Kt/V\) by means of direct quantification.
\(Kt/V_{id1}\), \(Kt/V\) by means of ionic dialysance and urea distribution volume (assumed to be 55% of dry weight).
\(Kt/V_{id2}\), \(Kt/V\) by means of ionic dialysance and anthropometric volume.
(a) Difference in comparison with the direct quantification method (gold standard).

Fig. 1. Difference between the \(Kt/V\) values calculated on the basis of ionic dialysance and urea distribution volume (assumed to be 55% of body weight) (\(Kt/V_{id1}\)) and those calculated by means of direct quantification (\(Kt/V_{dq}\), plotted against the \(Kt/V_{dq}\) values.
are always below the reference line shows that the Kt/V estimated using the conductivity method is systematically lower than that determined by means of direct quantification. The mean value of the difference was $-0.26 \pm 0.12$ which demonstrates an underestimate (inaccuracy) of 0.26 and an imprecision in individual Kt/V estimates of 0.24 or less.

The mean values of urea distribution volume calculated according to each of the three methods are shown in Table 2. When the urea distribution volume was assumed to be 55% of dry weight, the mean value was 17% higher than that obtained by means of direct quantification; and the same was true when anthropometric parameters were used.

Figure 2 shows the individual values of the urea distribution volumes obtained at each session, as a percentage of dry weight (V1), using anthropometric parameters (V2) and by means of direct quantification (Vdq). The urea distribution volumes calculated using the first two methods were significantly overestimated in comparison with those given by means of direct quantification ($P<0.01$). The mean value of Vdq was equivalent to 48% of body weight and the mean value of its coefficient of variability was 4.7 ± 2%.

The mean value of effective ionic dialysance was significantly lower than that of effective urea clearance: 155.0 ± 22.9 versus 175.0 ± 21.7 ml/min ($P<0.01$). Figure 3 shows the correlation between effective ionic dialysance and effective urea clearance and the equation used to derive effective urea clearance.

Figure 4 shows the difference between the individual values of Kt/V obtained at each session using V2 and ionic dialysance (Kt/Vid2) and those obtained by means of direct quantification (Kt/Vdq), plotted against the Kt/Vdq values. The fact that the values are always below the reference line shows that the Kt/V estimated on the basis of ionic dialysance and anthropometric urea distribution volume is systematically lower than that determined by means of direct quantification, without any specific pattern. The mean value of the difference was $-0.26 \pm 0.09$, which demonstrates an underestimate (inaccuracy) of 0.26 and an imprecision in individual Kt/V estimates of 0.18 or less.

The mean value of 1-min outlet dialysate flow was 515 ± 3.72 ml/min and the mean value of whole dialysate volume divided by the min of the dialytic session was 525 ± 9.08, with a ratio between Qdo/min and Vd/td of 0.98 ± 0.01. The mean value of dialysate urea

<table>
<thead>
<tr>
<th>Vdq</th>
<th>V1 Difference (a)</th>
<th>V2 Difference (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
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<tr>
<td>28.2 ± 2.4</td>
<td>32.7 ± 4.6</td>
<td>4.6 ± 3.6</td>
</tr>
</tbody>
</table>

Vdq, urea distribution volume calculated on the basis of direct quantification (litres). V1, urea distribution volume assumed to be 55% of dry weight (litres). V2, urea distribution volume calculated using anthropometric parameters (litres). (a), difference in comparison with the direct quantification method (gold standard.)

![Fig. 2. Individual urea distribution volumes at each session as calculated by assuming a fixed percentage of body weight (V1), by using anthropometric parameters (V2) and by means of direct quantification (Vdq).](https://academic.oup.com/ndt/article-abstract/11/10/2023/1815033)
Kt/V determination by conductivity

Fig. 3. Correlation between the individual mean values of ionic dialysance (ID) and effective urea clearance (KUeff).

concentration was 42 ± 9 mg/dl, with the 95% individual confidence limits ranging from 24 to 60 mg/dl.

The urea mass balance error was less than 5% in nine sessions in seven patients. By considering these sessions only, the final urea distribution volume (determined as the mean value between Vtdq and Vtk) was 27.9 ± 3.6 litres, equivalent to 49% of body weight. In the same sessions the ID/KUeff ratio was 0.89 ± 0.03.

Discussion

Dialysis dose quantification by means of Kt/V is of fundamental importance in prescribing and, above all, assessing the adequacy of the dialysis actually delivered, which is strictly related to patient morbidity and mortality. The direct quantification of removed urea (the gold standard for determining Kt/V) cannot be used on a routine basis since it requires the total or partial collection of spent dialysate; and on-line urea sensing devices are too expensive to be a real alternative at the moment. Furthermore, the urea kinetic models that require blood sampling are also unsuitable for routine application. It is therefore not surprising that great interest should be shown in a method which can allow Kt/V to be determined at each session without the need for any blood or dialysate samples, and at no additional cost.

Our results show that the Kt/V calculated using effective ionic dialysance (instead of effective urea clearance) and a urea distribution volume that is assumed to be 55% of body weight at the end of dialysis, was greatly underestimated in comparison with that determined by means of direct quantification. This difference is due to both the considerable overestimate of urea distribution volume (assumed to be a fixed percentage of body weight) and the underestimate of effective urea clearance (assumed to be equivalent to ionic dialysance). Moreover, the results did not improve when the urea distribution volume calculated by means of anthropometric parameters was used, since this was also considerably overestimated.

In our study, the ionic dialysance values were clearly lower than those of effective urea clearance, with an ID/KUeff ratio equal to 0.89 ± 0.04 (0.89 ± 0.03 when
considering the nine sessions with a urea mass balance error of less than 5%. There is indirect evidence to suggest that there may actually be a difference between the two parameters. It has been observed that the value of ionic dialysance can decrease during dialytic sessions performed using a high ultrafiltration rate, and a correlation has been found between the decrease in ionic dialysance and the decrease in plasma water flow at a constant blood flow [16]. On the contrary, no decrease in effective urea clearance has been observed, and blood water flow (the solvent for urea [7]) is not significantly reduced by intradialytic ultrafiltration. Consequently, although the urea and sodium diffusion constants are almost equal, ionic dialysance cannot be assimilated to urea clearance because of the difference in effective blood flow, which is lower for ionic dialysance and mainly represented by plasma water flow.

Our results are in contrast with those obtained by Petitclerc et al. [11], who reported good agreement between the two variables. They are also in contrast with Gotch et al. [17] who, using a Fresenius module and polysulphone dialysers, reported a ID/KUeff ratio equal to 1.00±0.67.

Since over- or underestimates of 1-min outlet dialysate flow and whole dialysate volume could lead to erroneous low or high estimates of ionic dialysance and effective urea clearance respectively, the difference between our results and those of Petitclerc could be simply due to inaccuracies in dialysate flow determinations. In our study, the ratio between Qdo/min and Vd/min was 0.98±0.01 ml/min; furthermore dialysate urea concentration was always within the optimal operative range of the determination methods. We can therefore exclude the possibility that ionic dialysance and effective urea clearance may have been artfully at variance in our study. Ebben et al. [18] have recently demonstrated an ‘in vitro’ ID/KU ratio equal to 0.92 or 0.94 (at QB 200 or 400 ml/min) when using cellulose acetate dialysers (the same membrane as that used in our study), but this became 0.98 or 1 (at QB 200 or 400 ml/min) when polysulphone dialysers were used. Since sodium is charged and urea uncharged, the authors suggest that these differences in sodium and urea transport may be due to differences in the surface charge of the membranes; it is therefore right to think that the correlation between ID and KUeff would also be dependent on the type of dialyser.

As far as urea distribution volume calculated on the basis of direct quantification is concerned, our results are at variance with the data previously published by Ellis et al. [19], who reported that Vdq is 53% of body weight as against the 48% found by us. The reliability of our Vdq measurements is supported by the low mean value of the coefficient of variability: 4.7±2%. Furthermore, in the nine sessions in which the urea mass balance error was less than 5%, the final urea distribution volume determined as the mean value between Vdq and V by means of the equilibrated single pool variable volume kinetic model was nearly equivalent to Vdq and corresponded to 49% of body weight.

At least one criticism can be made of the method adopted by Ellis et al. to calculate Vdq: the equation used assumes that body water volume remains the same during the session, and this leads to its being overestimated. On the contrary, we used an equation designed to calculate total body water volume at the end of a dialytic session. In a patient weighing 60 kg, Vdq would be 31.8 litres if it were equal to 53% of body weight, but would become 28.8 litres (corresponding to 48% of body weight) in the case of an ultrafiltration value of 3 litres, such as that generally used in our patients: our results are therefore not inconsistent with those previously reported by others.

In conclusion, although further studies are required to clarify the relationship between effective ionic dialysance and effective urea clearance (particularly in relation to the type of dialyser used), our results clearly suggest that they are not the same. Nevertheless the close correlation between the two parameters makes it easy to derive effective urea clearance from ionic dialysance. Since it is reasonable to assume that urea distribution volume is constant in steady-state patients, once this has been exactly determined by means of the measurement of ionic dialysance, it is possible to calculate Kt/V on-line at each session without the need for any blood sampling or laboratory examinations, and at no additional cost. The conductivity method seems to be very important because in everyday clinical practice it could provide an easily accessible and totally non-invasive means of monitoring the effective delivered dialysis at each dialytic session on-line, and adjusting the dose to ensure ‘adequate’, or even better, ‘optimal’ dialysis. In this way it could significantly improve chronic haemodialytic treatment.

Appendix

Instantaneous determination of effective ionic dialysance by means of Biofeedback Module

\[ ID = Q_{do} \times [1 - (C_{out1} - C_{out2})/(C_{in1} - C_{in2})] \]  
where ID = effective ionic dialysance (ml/min)

\[ Q_{do} = \text{outlet dialysate flow (ml/min)} \]

\[ C_{in1} \text{ and } C_{in2} = \text{two different values of dialysate conductivity at dialyser inlet} \]

\[ C_{out1} \text{ and } C_{out2} = \text{outlet dialysate conductivity at the two inlet conductivity values} \]

Determination of urea distribution volume by means of direct quantification (Vdq)

\[ V_{dq} = (C_d \times V_d - \Delta BW \times C_o - G \times t)/(C_o - C_t) \]  
where \( V_{dq} \) = urea distribution volume at the end of session (dry weight)

\( C_d \) = urea concentration (mg/ml) in whole spent dialysate

\( V_d \) = volume of whole spent dialysate (ml)

\( \Delta BW \) = difference between pre- and postdialysis weight (ml)

\( C_o \) = plasma urea concentration (mg/ml) at the start of the session
**Kt/V determination by conductivity**

\[
\begin{align*}
G &= \text{urea generation rate (mg/min)} \\
t &= \text{session length (min)} \\
C_t &= \text{plasma urea concentration (mg/ml) 30 min after the end of session} \\
\end{align*}
\]

**Determination of urea generation rate (G) by means of direct quantification**

\[
G = \frac{[C_{o2} \times V_{o2} - C_{t1} \times V_{t1}]}{T} \tag{3}
\]

where \(C_{o2}\) = plasma urea concentration (mg/ml) at the start of the subsequent session

\(V_{o2} = V_{tdq} + \Delta BW\)

where \(V_{tdq}\) = urea distribution volume at the end of the previous session (ml)

\(\Delta BW\) = difference between previous post- and actual predialysis weight

\(C_{t1}\) = plasma urea concentration (mg/ml) 30 min after the end of previous session

\(V_{t1} = V_{tdq}\)

\(T = \text{interdialytic time (min)}\)

**Determination of 'mean' effective urea clearance by means of direct quantification**

\[
K_{eq} = \frac{Cd \times Vd}{(C_{pw o} - C_{pw t}/\ln(C_{pw o}/C_{pw t})) \times t} \tag{4}
\]

where \(C_{pw o}\) = plasma water urea concentration (mg/ml) at the start of dialytic session

\(C_{pw t}\) = plasma water urea concentration at the end of dialytic session (after QB reduced to 50 ml/min for 3 min)

\(t = \text{session length (min)}\)

**Calculation of 'instantaneous' diffusive urea clearance (K)**

\[
K = Qe \left( e^{z-1}/(e^{z-1}) - Qe/Qd \right) \tag{5}
\]

where \(Qe\) = total blood water flow = QB \times 0.85

\(QB\) = blood flow (ml/min)

\(z = (KoA/Qe) \times (1 - Qe/Qd)\)

\(KoA = \text{dialyser permeability coefficient (ml/min)}\)

\(Qd = \text{dialysate flow (ml/min)}\)

**Calculation of 'effective' urea clearance (UK)**

\[
UK = K \times C_a/C_s \tag{6}
\]

where \(C_a\) = plasma urea concentration (mg/dl) at dialyser inlet

\(C_s\) = plasma urea concentration at dialyser inlet after QB reduced to 50 ml/min for 3 min, corresponding to systemic concentration

**Calculation of urea distribution volume by means of the SPVV kinetic model (V_{ik})**

\[
V_{ik} = \frac{Qf \times t \times [1 - Y^{Qf(K-Qf)}]}{1 - \frac{Qf}{K}} \tag{7}
\]

where \(Qf\) = ultrafiltration volume (ml/min)

\(t = \text{session time (min)}\)

**Calculation of net urea removal by means of direct quantification (UR_{dq})**

\[
UR_{dq} = (V_{o} \times C_{o}) - (V_{t} \times C_{t}) \tag{8}
\]

where \(V_o\) = whole spent dialysate volume (ml)

\(C_o\) = dialysate urea concentration (mg/ml)

\(G = \text{urea generation rate (mg/min)}\)

\(t = \text{session length (min)}\)

**Calculation of net urea removal by means of the SPVV kinetic model (UR_k)**

\[
UR_k = (V_{o} \times C_{o}) - (V_{t} + \Delta BW) \times C_t \tag{9}
\]

where \(V_{t} = V_{ik}\) (ml)

\(V_o = V_{tk} + \Delta BW\) (ml)

\(\Delta BW\) = difference between pre- and postdialysis weight (ml)

\(C_o = \text{plasma urea concentration (mg/ml) at the start of session} \)

\(C_t = \text{plasma urea concentration (mg/ml) 30 min after the end of session} \)

**Calculation of mass balance error (MBE%)**

\[
MBE\% = \frac{2 \times UR_{dq} - UR_k}{(UR_{dq} + UR_k)} \times 100 \tag{10}
\]

**References**


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