Blood and Dialysate Flow Distributions in Hollow-Fiber Hemodialyzers Analyzed by Computerized Helical Scanning Technique

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Abstract. The efficiency of a hemodialyzer is largely dependent on its ability to facilitate diffusion between blood and dialysis solution. The diffusion process can be impaired if there is a mismatch between blood and dialysate flow distribution in the dialyzer. This article describes the distribution of the blood and dialysate flows in hollow-fiber hemodialyzers analyzed with a computerized scanning technique. Blood flow distribution was studied in vitro by dye injection in the blood compartment during experimental extracorporeal circulation using human blood with hematocrit (Hct) adjusted at 25 and 40%. Sequential images were obtained with a helical scanner in a 1-cm-thick fixed longitudinal section of the dialyzer. Average and regional blood flow velocity and wall shear rates were measured by using the reconstructed imaging sequence. The method allowed the calculation of single-fiber blood flow and single-fiber wall shear rate (SF wSh) in different regions of the hemodialyzer. In 38 patients on chronic hemodialysis, creatinine and phosphate clearance displayed a significantly negative correlation with Hct \( P < 0.05 \), but this correlation was not found for urea, although a trend toward reduction could be observed. The suggested explanation of this phenomenon is the significant reduction in effective plasma water flow across the hemodialyzer in presence of a progressive rise in Hct. The second explanation for this phenomenon may be found in the nonhomogeneous distribution of blood flow within the fibers observed at the sequential imaging. This, in fact, could also explain the negative trend observed for urea. At higher Hct levels, single-fiber blood flow velocity and SF wSh were significantly lower in the fibers situated at the periphery of the bundle. At the same time, SF wSh tended to decrease in peripheral fibers, showing a value near half of that observed in the central fibers of the bundle (165 versus 301 s\(^{-1}\)).

A similar technique was used to study the flow distribution in the dialyzer compartment in three different types of hemodialyzers with characteristic dialysate compartment design: (A) standard configuration; (B) space yarns (spacing filaments preventing contact between fibers); and (C) Moiré structure (wave-shaped fibers to prevent contact between adjacent fibers). Clinical sessions of hemodialysis were also carried out to measure blood- and dialysate-side urea clearances in the different hemodialyzers. Macroscopic and densitometric analysis revealed that flow distribution was most homogeneous in the dialyzer with Moiré structure (type C) and least homogeneous in the standard dialyzer (type A). Space yarns (type B) gave an intermediate dialysate flow distribution. Urea clearance (\( P < 0.001 \)) increased significantly with types B and C, compared with the standard dialyzer. Type C had the highest clearances, although they were not significantly greater than type B. In conclusion, a significant blood-to-dialysate flow mismatch may occur in hollow-fiber hemodialyzers due to uneven blood flow distribution or a dialysate channeling phenomenon external to the fiber bundle. Improvement in dialyzer design may overcome these problems, at least in part.

Hemodialyzers are conceived as special devices to achieve optimal solute and water exchanges between blood and dialysate (1–5). The optimization of countercurrent flow and the improved hydraulic properties of dialytic membranes allowed the development of remarkably efficient hemodialyzers in the early 1970s. For many years, dialyzers were then designed according to the original concept, and only a few original innovations have been proposed in this field. Only recently, new methods of analysis, newer manufacturing processes, and new requirements of efficiency and performance have spurred a renewed interest in improving the design of each component of the hemodialyzer.

Small solute removal is primarily obtained by diffusion. Convection represents an additional mechanism that is mostly important for larger molecules. The efficiency of a hemodialyzer is therefore dependent on its ability to facilitate the diffusion process (6–9). Diffusion is affected by blood and dialysate flow rates, temperature, surface area of the dialyzer, and thickness of the membrane. Assuming all other factors are constant, the diffusion process is basically dependent on the concentration gradient between blood and dialysate (10–11).
This is strongly affected by the blood and dialysate flow rates and by the distribution of the countercurrent flows in their relative compartments. It is evident that any possible mismatch between blood and dialysate flow distributions can create a significant reduction in the efficiency of the filter (10). In some cases, blood flow distribution may be less than optimal due to blood viscosity properties or to a poor distribution of the flow at the blood inlet port (11–12). In this case, the external fibers of the bundle may be penalized by a lower flow velocity compared with the fibers located in the central region of the bundle. On the other hand, fiber packing density may be higher in the central region of the bundle, and dialysate flow may be limited in that region by an increased resistance. Under these circumstances, dialysate tends to flow at higher speeds in those regions of the filter where blood flow velocity is minimal and vice versa (13). This effect may be the cause of inconsistent performances of the hemodialyzer, and resultant clearance values may be lower than those expected from theoretical calculations (14).

This article describes the impact of blood-to-dialysate flow mismatch on hemodialyzer efficiency, analyzing the blood and the dialysate compartments separately. The flow distribution in the blood compartment of hollow-fiber hemodialyzers was studied in vitro at different flow rates by using human blood adjusted at different hematocrit (Hct) values. Solute clearances were measured in vivo in a population with different levels of Hct and blood viscosity.

As a second step, the dialysate compartment effect was studied in vitro by comparing hemodialyzers with different dialysate compartment design. Standard design was compared with two modified dialysate compartment designs. One includes the presence of space yarns between the fibers to prevent the contact of adjacent fibers, and the second features a wave design of the hollow fibers (Moiré structure), which makes adhesion of adjacent fibers less likely to occur (Figure 1). The analysis included a flow distribution evaluation by helical computed tomography scan and a clearance study for different molecules.

Materials and Methods

Blood Compartment

In Vivo Study. Thirty-eight hemodialysis patients (20 men, 18 women) with mature functioning arteriovenous fistula participated in the study. Their mean age was 58 ± 12 yr, and they had been receiving dialysis treatments for 35 ± 14 mo with an average duration of 3.5 h 3 times per wk. In each patient, Hct was determined at the beginning of the hemodialysis session.

Standard midweek hemodialysis sessions were analyzed in this study. Bicarbonate dialysate and 1.3-m² hollow-fiber triacetate hemodialyzers (Sureflex SF130E; Nipro, Osaka, Japan) were used. The

Figure 1. Representation of the technique used for the imaging acquisition. (Left panels) the position of the filter in the gentry (top, blood compartment test; bottom, dialysate compartment test). The first acquired image is the topogram (right panel), which represents a cross section of the hemodialyzer. After injection of the dye, the imaging sequence is acquired and subsequently reconstructed. The densitometric analysis is finally carried out in the subsequent images obtained in the studied layer (1-cm-thick) corresponding to a longitudinal section of the filter.
dialysate contained 139 mmol/L sodium, 1 mmol/L potassium, 108 mmol/L chloride, 1.75 mmol/L calcium, 0.5 mmol/L magnesium, 36 mmol/L bicarbonate, and 3 mmol/L acetate. Blood flow was 300 ml/min, and dialysate flow was 500 ml/min.

Clearance was calculated from both the blood side and the dialysate side by using the following formulas:

\[ K_b = \frac{(Q_{Bwi} \times C_{bi}) - (Q_{Bwo} \times C_{bo})}{C_{bi}} \]
\[ K_d = \frac{(Q_{do} \times C_{do})}{C_{bi}} \]

Where \( K \) is clearance in ml/min, \( K_b \) is the clearance from the blood side, \( K_d \) is the clearance from the dialysate side, \( Q_{Bwi} \) is blood water flow at filter inlet in ml/min, \( Q_{Bwo} \) is blood water flow at filter outlet in ml/min, \( C_{bi} \) is arterial concentration of solute in mmol/L, \( C_{bo} \) is the venous concentration of solute in mmol/L, \( Q_{do} \) is dialysate flow at filter outlet in ml/min, and \( C_{do} \) is solute concentration in the spent dialysate in mmol/L. The average values of blood- and dialysate-side clearance were taken as a reference for each patient. When mass-balance error was >5%, the test was discarded and repeated. Urea clearance calculation was performed by using blood water flow, and creatinine clearance calculation was performed by using plasma water flow (11). Clearances were measured at 30 (T30) min after the start of the dialysis session. Blood flow rate, dialysate flow rate (Q D ), and transmembrane pressure were kept constant during the period of sampling. Arterial and venous blood samples were drawn simultaneously. A constant time period was maintained between blood drawing and centrifugation to ensure the same degree of equilibration between intracellular and plasma compartments in vitro. Samples were analyzed for urea and creatinine by using the standard enzymatic assays. Dialysate collection time for the dialysate-side clearance calculation was 10 min.

**In Vitro Study.** Blood flow distribution was analyzed by dye injection into the blood compartment of the same dialyzers used for the clearance study during an in vitro experimental circulation. Thermostated human blood with Hct adjusted at 25% and 40%, respectively, was used for two different sets of analysis. Sequential imaging was obtained with a computerized helical scanner (X-press 120, Toshiba, Tokyo, Japan) in a 1-cm-thick longitudinal section of the hemodialyzer (Figure 1). The reconstructed imaging sequence allowed for measurement of average single-fiber blood flow (SF Qb) and wall shear rate (SF wSh) in different regions of the fiber bundle.

Hemodialyzers were held in a vertical position by a support, and blood entered from the blood port in the bottom. Blood was recirculated at 300 ml/min from and to a reservoir containing 500 ml of blood. In the two sets of experiments, blood Hct was adjusted to 25% and 40%, respectively, by means of compatible plasma. Protein concentration was maintained at 6 g/dl. Each experiment was repeated three times. When the blood flow had reached steady state, one vial of dye (Iopamiro, Bracco, Italy; dilution 4:1) was injected by a pump in

![Figure 2](image-url). Representation of the proximal portion of the hemodialyzer during the injection of the dye. The blood compartment test is described (left panel). Two densitometric profiles (DP1 and DP2) that show the flow distribution in two subsequent images (t1 and t2) are described. Analysis of density profiles are carried out at different regions of interest (ROI 1, ROI 2, and ROI 3). When the blood with the dye enters the blood port of the hemodialyzer, a flow distribution curve starts to build up. Regional velocity is calculated between two different ROI and the time required for a given point (Cr, central; Pr, peripheral) to reach the same relative increase in density. Relative densitometric changes are measured in Hounsfield units and permit the subtraction of the densitometric values of the fibers before the injection of the dye. Only densitometric changes due to flow are measured in the analysis. The same analysis is performed for the dialysate compartment on the right panel. Maximal velocities are however obtained in the peripheral regions of the compartment.
the arterial line of the circuit over a period of 30 s. Computed tomography scan recording started immediately thereafter at a rate of 1 scan/s on a 10-mm-thick fixed layer. At the end of the exam, image reconstruction was achieved via software (Toshiba X-press 120) and image evaluation was carried out by densitometric analysis in specific regions of interest (ROI). As reported in Figure 2, we selected a sequence of cross-sectional segments spaced 1 cm apart along the length of the hemodialyzer. Average flow velocity and average SF wSh was calculated as reported in Figure 2. Regional flow velocity, SF Qb, and SF wSh were calculated from the sequential profiles of density achieved in the imaging sequence. Densitometric values in selected sequential ROI were used to describe the progression of flow through the filter and to calculate regional flow distribution parameters. We selected one central region and two peripheral regions 1-cm-wide corresponding to 1 cm² on the cross section of the hemodialyzer (layer thickness, 1 cm). Considering the fiber packing density provided by the manufacturer (46%) and the cross-sectional surface of the studied region (1 cm²), we calculated that the number of fibers analyzed was 1100/cm² in each specific sample region. The sample was therefore sufficiently representative of the average flow condition in the studied region. Regional velocity, measured in Hounsfield units, was calculated from the time required by two subsequent ROI to achieve the same level of density. The density profile is generated by the distribution of the dye in the fiber bundle. In the case of fibers with higher flow velocity, two subsequent points of these fibers will reach the same density value much earlier compared with fibers in which the flow velocity is slower. When the regional velocity is determined, SF Qb and SF wSh can be easily derived by using the formulas described in Figure 2.

The visual effect of a different velocity distribution can also be achieved by the density profiles recorded at the same time from the dye injection in similar ROI. The shape of the densitometric curve describes the flow distribution and the relative flow velocity in the central and peripheral regions of the hemodialyzer.

**Dialysate Compartment**

**In Vivo Study.** Eighteen hollow-fiber 1.3-m²² hemodialyzers were tested for the study. Six dialyzers (type A) were equipped with the standard fiber bundle (PAN 65DX; Asahi Medical, Tokyo, Japan), six dialyzers (type B) were equipped with spacing filaments external to the fibers (PAN 65SF; Asahi Medical, Tokyo, Japan), and six dialyzers (type C) that presented the same surface area and fiber packing density of the previous dialyzers had waved fibers to obtain the so-called Moiré Structure (FP 130; Nissho-Nipro, Osaka, Japan).

Each dialyzer was studied in three different patients with the following randomized sequence: patient 1 (B, A, and C); patient 2 (A, B, and C); patient 3 (C, A, and B). In these patients, three consecutive dialyses were carried out with identical operational parameters (Qb, 300 ml/min; Qd, 500 ml/min), using the three different types of dialyzers (A, B, and C). In each session, blood- and dialysate-side urea clearances were measured at 30 min of treatment according to the same protocol described for the blood compartment test.

**In Vitro Study.** Three dialyzers of each type were studied **in vitro** in the radiology department using the same equipment used for the blood compartment test. The dialyzers were placed in a vertical position (dialysate inlet in the bottom) in the gantry of the machine (Figure 1, bottom left). The blood compartment was filled with dialysate and closed hermetically so that no influx or outflux of water was impossible. The dialysate compartment was also primed with dialysate to avoid the presence of air bubbles. The scanning sequence was performed with the characteristics described for the blood compartment test, except that the dye was injected in the dialysate compartment and the flow was 500 ml/min.

Data were elaborated to achieve 20 reconstructed images with a thickness of the section of 10 mm. The images corresponded to the dynamic sequence of the dye distribution inside the dialyzer. Channeling phenomena can be identified by significant differences in density from the center to the peripheral regions of the dialyzer; therefore, a careful analysis of relative density in the same ROI analyzed for the blood compartment was carried out (Figure 2, right panel).

**Results**

**Blood Compartment**

**In Vivo Study.** Predialysis Hct values in the studied HD patients ranged from 26.5 to 46.7% (average, 37 ± 4.8%), and Hb from 10.5 to 14.9 g/dl. Ultrafiltration rate in the dialysis sessions ranged between 11 and 16 ml/min (10.8 ± 4.6 ml/min). Clearances of solutes averaged 235 ± 18 ml/min for urea, 138 ± 24 ml/min for creatinine, and 149 ± 26 ml/min for phosphate.

Urea clearance was not significantly related to Hct levels, although a trend could be observed with a slight reduction in patients with higher Hct (Figure 3). Both creatinine and phosphate clearances negatively correlated (P < 0.05) with Hct. It seems apparent that clearances of solutes confined to plasma water were more affected by changes of Hct than those of solutes freely diffusing across the red cell membrane.

**In Vitro Study.** A remarkable difference of density profiles was displayed by the hemodialyzers tested with Hct of 25% and 40%, respectively (Figure 4). The visual effect is dramatic. From the subsequent images, the different shape of the parabolic profile in the two experimental conditions can be clearly seen. In conditions of Hct of 25%, the differences in density between the central and the peripheral regions are less evident. In conditions of Hct of 40%, a remarkable difference can be observed between the peripheral regions and the central region of the bundle, and a parabolic profile is observed. The average calculated blood flow per fiber was 0.0031 ml/min, and the average calculated flow velocity per fiber was 1.69 cm/s. With Hct of 25%, the flow velocity of blood in the central fibers of the filter was 1.91 cm/s, and in peripheral fibers was 1.3 cm/s. Wall shear rate in the central fibers was 764 s⁻¹, and a value of 520 s⁻¹ could be observed in peripheral fibers. At Hct of 40%, the discrepancy of flow distribution became even more evident. Flow velocity and wall shear rates were higher in the central fibers (2.4 cm/s and 764 s⁻¹, respectively) and lower in the peripheral fibers (0.8 cm/s and 320 s⁻¹, respectively) compared with the results obtained with Hct of 25%.

**Dialysate Compartment**

**In Vivo Study.** The clearance values for the studied filters are reported in Figure 5. The differences between dialyzer types A and B are significant, with increased urea clearances being observed in the dialyzers equipped with spacing filaments. A further advantage, although NS from type B, can be observed in type C dialyzers. The obtained values may be due
to the reduction of stagnant layers at the dialysate/membrane interface and an increased availability of surface area available for the exchanges. The same effect is displayed for creatinine and phosphate, which shows that diffusion still represents an important mechanism of transport also for molecules larger than urea.

**In Vitro Study.** The three dialyzer types displayed a significantly different radiologic pattern. In particular, the dialyzers with the space yarns and the Moiré structure displayed a more homogeneous distribution of the dye. The increased homogeneity of dialysate flow distribution in the dialyzers with the Moiré structure was confirmed at the computerized densitometric analysis of the selected ROI. This offered a further series of detailed information. The graphic representation of the densitometric profiles achieved in the three different dialyzers is reported in Figure 6. It can be seen that remarkable differences in density are present in the standard dialyzer. The pattern is also not completely homogeneous in the dialyzers with spacing yarns, but the differences between the central and the peripheral regions are remarkably attenuated. This pattern is further improved in the dialyzers with the Moiré design. In Figure 7, a comparative calculation of the relative dialysate flow velocity in the peripheral and central regions of each type of dialyzer is reported. Again, the optimal design of the dialysate compartment would lead to a central and peripheral velocity of the flow close to the average flow velocity calculated in the whole dialyzer. This result is approached only in the case of the Moiré design, and it is definitely not achieved in hemodialyzers with a standard configuration. The spacing yarn design achieves an intermediate pattern with some benefits compared with the standard design.

**Discussion**

The uremic syndrome is characterized by the retention of a host of solutes that interfere with various biochemical functions. Over the past decade, much clinical research has been carried out on the adequacy of dialysis, mainly focusing on the clearance of the low molecular weight substances like urea and with much less consideration for the middle molecular weight substances, such as beta-2-microglobulin (15). Moreover, treatment of renal anemia by recombinant human erythropoietin (EPO) has increased dramatically the average Hct in the dialysis population. Although positive effects were expected on cardiovascular function, there has been increasing concern that increasing Hct values beyond a certain level will adversely affect dialyzer clearance necessitating a modification in dialysis therapy. Besarab *et al.* (16) reported that, although changes in dialyzer clearances after EPO treatment were NS, dietary compliance required careful monitoring. Other authors (17–18) found that there were slight decreases in clearances of creatinine, potassium, and phosphate in patients receiving either high-flux or conventional dialysis during treatment with EPO. In other studies (19–20), creatinine and phosphate clearances significantly decreased in the presence of high Hct values, although urea clearance was minimally affected. Burr and Martin (21) noted that dialysis efficiency for creatinine decreased by approximately 10% in patients with high Hct.

Our study showed that creatinine and phosphate clearances negatively correlated with Hct levels and that urea clearance only displayed a negative trend. This is a finding that is in agreement with previous studies (19,20,22). Urea is a highly diffusible molecule and freely mobile between the extracellular...
and intracellular compartments. As a consequence, urea should not be significantly affected by changes in the plasma volume/red cell volume ratio. On the other hand, creatinine and phosphate are slowly moving across the red cell membrane, and for dialytic purposes they can be considered confined to plasma water. Relative plasma volume is reduced when Hct increases, and this may decrease the delivery of creatinine and phosphate to the hemodialyzers due to a decrease in effective plasma flow.

This appears to be the most logical explanation, but our *in vitro* results seem to suggest a further possible effect played by an impaired blood flow distribution that occurs in the dialyzer when Hct increases.

Blood is a concentrated suspension of red cells in an aqueous electrolyte-protein solution, which shows a viscoelastic property (23). The viscoelasticity of the blood is traceable to the elastic red cells. When the red cells are at rest, they tend to aggregate and stack together. To flow freely, the aggregates must disintegrate and the cells must undergo elastic deformation and orientation to each other. This process depends on several factors, including Hct, plasma proteins, and fibrinogen (24). The blood flow in a narrow vessel with inner diameter <300 microns is determined by how the cells glide past each other and how interaction between cells and vessel walls take place (25). Therefore, insight into the blood flow mechanics within the dialyzer is needed to understand the complicated effects of increasing Hct levels.

One should consider the important function of the arterial blood port of the hemodialyzer. This component is crucial for ensuring a good distribution of blood into the fibers. The presence of turbulence, dead spaces, or preferential pathways might interfere with a good distribution, and peripheral fibers may be penalized in terms of flow delivery.

Assuming a physiologic difference in flow delivery between

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**Figure 4.** Selected images recorded in conditions of Hct 25% (top panels) and Hct 40% (bottom panels). The densitometric profile describing flow distribution in the selected ROI is highlighted. A typical profile can be observed. The parabolic bimodal shape becomes more evident in the images obtained at Hct 40%, describing a further alteration of the flow distribution in the hemodialyzer.

**Figure 5.** The bars describe the average values of urea, creatinine, and phosphate clearance obtained with the three types of hemodialyzer. A significant increment in clearance could be obtained in the space yarns dialyzers and in dialyzers with the Moiré design compared with the dialyzers with the standard configuration. The values between Moiré design and the space yarns design hemodialyzers were NS.
the central (higher) and the peripheral (lower) regions of the bundle, there may be an additional effect inducing a further reduction of flow velocity in the peripheral fibers. Due to the hydraulic design of the hemodialyzer, transmembrane pressure gradient will be equally applied to all fibers of the bundle. If the single-fiber blood flow is slightly lower from the beginning in the peripheral regions of the bundle, these fibers will experience a slightly higher filtration fraction. In fact, for the same permeability coefficient and the same transmembrane pressure gradient, equal amounts of ultrafiltration will be produced in all fibers. However, peripheral fibers tend to have a lower blood flow per fiber; therefore, this will result in higher single-fiber filtration fraction and higher hemoconcentration in the fiber. This in turn will result in an increase in blood viscosity and a possible increase of the resistance to flow in those specific fibers. This phenomenon may contribute to a further reduction in flow velocity and a new steady state profile. The phenomenon only leads to a new steady state profile and not to a progressive obstruction of the peripheral fibers for two reasons. One is the lower wall shear rates that are present in these fibers and the consequent formation of a boundary layer that limits ultrafiltration. The second is linked to a progressive increase in the oncotic pressure that is generated by plasma proteins that act against ultrafiltration. Assuming these considerations are true, one could expect a different flow distribution profile within the hemodialyzer in the presence of constant Hct and blood flow but variable levels of ultrafiltration.

Considering the rheologic properties of blood and its typically nonNewtonian behavior, alternative hypotheses can be formulated. Blood is a fluidized suspension of red blood cells that has viscoelastic properties that reflect the cumulative effects of plasma viscosity and Hct. The smaller the velocity and the shear rate applied to blood, the higher its viscosity. Therefore, one can speculate that the lower flow velocity observed in the peripheral fibers further aggravates the flow-dynamic conditions because of a relative increase in blood viscosity in those fibers.

In summary, blood is distributed nonproportionally in the hemodialyzer. This uneven distribution is strongly affected by the level of Hct. The final effect is reflected on efficiency and solute clearances. We assume that this effect can be individualized to the patients, because it can be affected by several factors, e.g., the degree of ultrafiltration, the presence of stiff erythrocytes, and the blood flow rate. Hemodialyzer design has been quite constant over the last 20 yr. The average Hct of patients has, however, increased significantly. Therefore, a

Figure 6. The results obtained with the three different hemodialyzers are reported. Two ROI are analyzed in sequence by the software of the helical scanner, and the reported curves represent the densitometric profiles achieved in the dialysate compartment at two different times. It is evident that as the flow distribution pattern builds up, the standard configuration displays a nonhomogeneous distribution of the dye with higher flow velocity in the peripheral regions of the dialyzer. The pattern is improved with the space yarns configuration, but the best results are obtained with the Moiré design.
packed beds involve the fundamental principle that governs the flow of fluids through a packed bed. As discussed in detail in a recent publication (29), the cause the undesirable phenomenon of so-called channeling of flow, resulting in wide variations of local flow velocity. This may occur in tortuous capillary tubes. In the case of the dialysate compartment, some wide-diameter tortuous capillary tubes. In this case, the packed bed can be approximated to a bundle of fibers. The fibers are not tightly packed; in packed beds, the packing structure of the hollow fibers is usually quite complex, and the resultant flow pattern external to the fibers is extremely complicated. In well-packed columns, the diversity of channel diameters and of velocities in the individual channels is small. If the ratio of the tube diameter to the particle diameter is less than 100, this may have a significantly positive effect on the flow distribution profile.

The flow distribution in the dialysate compartment can be theoretically modeled using equations of physical chemistry and transport (27–28) and can be assimilated to the flow distribution in packed beds. As in packed beds, the packing structure of the hollow fibers is usually quite complex, and the resultant flow pattern external to the fibers is extremely complicated. In well-packed columns, the diversity of channel diameters and of velocities in the individual channels is small. In this case, the packed bed can be approximated to a bundle of tortuous capillary tubes. In the case of the dialysate compartment of a hollow-fiber hemodialyzer, some wide-diameter channels and gaps in the packing structure may be present, resulting in wide variations of local flow velocity. This may cause the undesirable phenomenon of so-called channeling of the flow. As discussed in detail in a recent publication (29), the fundamental principle that governs the flow of fluids through packed beds is Darcy’s law. The free cross section of the dialysate compartment bed (total internal area of the case-total area occupied by the fibers) consists of the interfiber gaps (interparticle porosity) and constitutes the fluid pathway external to the fibers. The dimension of the specific permeability of the compartment is \( \text{cm}^2 \) but it could be given in Darcy units (1 darcy = \( 10^{-8} \) cm\(^2\)). Unfortunately, the bundle can be concentrated and packed in the central region of the dialyzer, and low resistance pathways can be created in the more peripheral regions of the compartment. This results in a greater flow velocity in the peripheral regions while a significant stagnation can be observed in the central region. In this case, the specific permeability of the interfiber space of the bundle in the central region becomes much smaller than that observed in the peripheral regions and the efficacy of the countercurrent flow is impaired.

The most uniform flow profile in packed beds can be obtained when beds are packed tightly with spherical particles of equal size. If the ratio of the tube diameter to the particle diameter is less than 100, this may have a significantly positive effect on the flow distribution profile.

In our system, the fibers and their external surface substitute the particles of a bed. The fibers are not tightly packed; therefore, preferential fluid pathways may be generated. This explains why the packing density of hollow fibers is an important parameter in the design of a hemodialyzer. Furthermore, it seems that special configurations that are designed to prevent close contact of adjacent fibers may induce a significant improvement on the flow distribution.

This study has permitted the evaluation of the possible effect of new solutions oriented to the improvement of the dialysate pathway configuration. In particular, the use of space yarns external to hollow fibers may help in reducing the negative effects that are due to dialysate channeling. A more homogeneous distribution of the dialysate mixed with a contrast medium was demonstrated by our radiologic technique, using the helical scanning procedure. Further advantages seem to be obtained by the waved configuration of the hollow fibers in the bundle, creating the so-called Moiré structure.

The optimization of dialysate distribution in the modified hemodialyzers is also confirmed by an improved performance in terms of urea clearance. This suggests a definite improvement of the diffusion processes inside the dialyzer due to an optimization of the countercurrent effect on blood-to-dialysate solute gradients. Further advantage might be represented by the dissipation of the boundary layers due to fiber undulation.

The new radiologic technique described in this paper seems to be extremely useful in evaluating the flow distribution in either the blood or the dialysate compartments. It offers a detailed analysis of the regional flow velocity and opens the possibility of detailed controls of further future modifications of the hemodialyzer design (30).

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