Mass Transfer Coefficients in Hollow Fiber Dialyzers

J. A. Baker, J. O. Osburn, and R. L. Lawton
Departments of Chemical and Materials Engineering and Surgery
University of Iowa, Iowa City, Iowa 52240

ABSTRACT

A method for determination of mass transfer coefficients in hollow fiber membrane dialyzers is described. The procedure makes use of a hollow fiber dialysis cascade to obtain length concentration profiles experimentally. The mass transfer coefficients may be related to various mass transfer resistances.

INTRODUCTION

Mass transfer coefficients for aqueous solutions may be determined experimentally by the use of a hollow-fiber dialysis cascade consisting of several hollow-fiber dialyzers connected in series. The method is experimentally simple and rapidly gives one a great deal of data. By varying blood-side or dialysate-side flow rates, mass transfer coefficients may be determined for either side independently of the other side. Results are presented for the dialysis of aqueous sodium chloride solutions. The hollow-fiber dialyzers used were Dow Cordis Model 3 artificial kidneys.*

EXPERIMENTAL

The hollow-fiber dialysis cascade is shown in Figure 1. The Dow Cordis artificial kidney is designed so that the blood-side fluid flows through the inside of the hollow fibers. Characteristics of the Dow Cordis kidney are shown in Table 1. Connections between units were made with tygon tubing. Mercury manometers and rotameters were placed in the inlet fluid lines to monitor pressures and flow rates. A dilute solution of aqueous sodium chloride of concentration 0.094 M was used as the blood-side fluid while distilled water was used as the dialysate-side fluid. Solutions were contained in five-gallon carboys and fed to the unit by pulsatile pumps. Recycle lines from the pump discharge lines back to the carboys allowed for any combination of flow rates to be obtained.

TABLE 1
Characteristics of the Dow Cordis Model 3 Hollow-Fiber Hemodialyzer

DESCRIPTION: A hollow-fiber bundle contained in a cylindrical plastic shell, the hollow fibers being potted in silicone rubber.
DIMENSIONS: 21.6 cm long by 7 cm in diameter.
MEMBRANE: 11,000 hollow fibers made of regenerated cellulose.
Effective length: 13.5 cm; inside diameter: 225 microns.
Wall thickness: 30 microns; effective surface area: 1 square meter.
PRIMING VOLUMES: Blood side: 95 ml; dialysate side: 100 ml.
FLOW RESISTANCE: 0.175 mm Hg/ml-min for blood in blood-side compartment.
ULTRAFILTRATION RATE: 135 ml/hr-min Hg.

From each fluid stream of the cascade, six samples were taken for analysis, sample ports being located after each hollow-fiber unit. Sample ports consisted of plastic tees inserted into the tygon tubing connecting the individual units with the sample taken by releasing a pinch clamp on a drain line. Samples were taken after steady-state conditions had been obtained, usually 15-20 minutes after flow rates had been set.

Analysis for sodium ion was made by use of an Instrumentation Laboratory Flame Photometer Model 143. The temperature of the solutions used was 23°C. Flow rates varied from 150 to 250 ml/min. for the blood-side fluid and from 250 to 600 ml/min. for the dialysate-side fluid. This is the normal range of operating flow rates for the Dow Cordis kidney. The cascade was operated in a counter current manner.

*The Cordis Corp., Miami, Florida.

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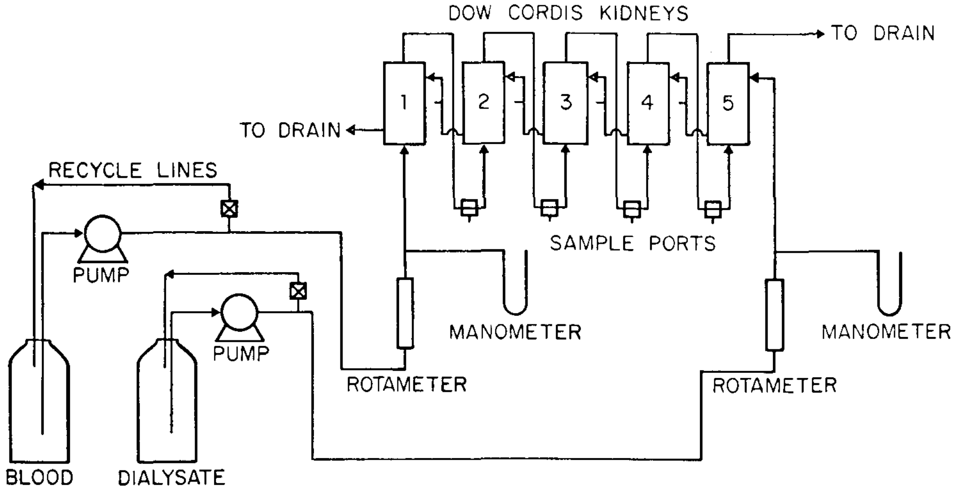
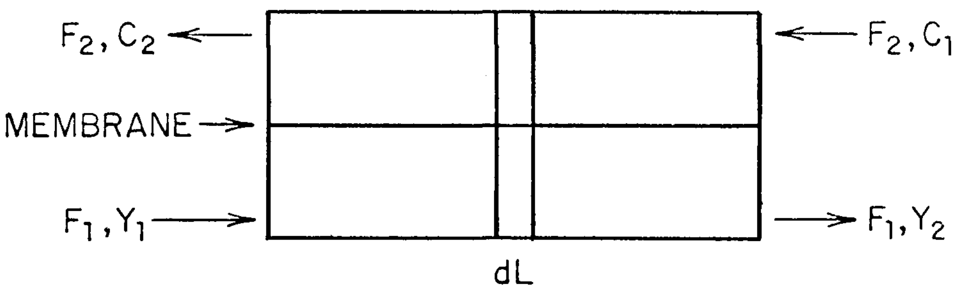


FIGURE 1

Hollow Fiber Dialysis Cascade



F_1 = DIALYSATE FLOW RATE
Y_1 = INLET DIALYSATE CONCENTRATION
Y_2 = OUTLET DIALYSATE CONCENTRATION
F_2 = BLOOD FLOW RATE
C_1 = INLET BLOOD CONCENTRATION
C_2 = OUTLET BLOOD CONCENTRATION
L = MEMBRANE LENGTH

FIGURE 2. DIALYSIS CELL SCHEMATIC DIAGRAM

CALCULATION PROCEDURE

From a plot of the concentrations in the blood and dialysate-side fluids versus length, the mass transfer coefficient may be determined for each blood-side or dialysate-side velocity and the following development explains how these coefficients are found: The dialysis cascade as shown in Figure 1 may also be schematically represented in Figure 2. A series of concentration profiles for a dialysate-side flow rate of 400 ml/min. and blood-side flow rates ranging from 150 to 250 ml/min. is shown in Figure 3.

A mass balance over a section dL of the cell (dialysate side) gives the following:

$$F_1\, dY = K_0 A\, (C\text{-}Y)\, dL \qquad (1)$$

where A = membrane area per length of cascade

K_0 = overall mass transfer coefficient, cm/min.

The total amount of solute transferred into the dialysate fluid may be found from a direct integration of the left-hand side of equation (1) to give:

$$F_1\, dY = F_1\, (Y_2\text{-}Y_1)$$

then $F_1\ (Y_2\text{-}Y_1) = K_0A\ (C\text{-}Y)\ dL$ and by integration of the right-hand side of the equation, the overall mass transfer coefficient may be determined. This integration is done by integrating a plot of (C-Y) versus L by use of Simpson's rule. The values for (C-Y) are determined from the concentration-length profiles.

The overall mass transfer resistance is the reciprocal of the overall mass transfer coefficient and this resistance may be represented as a sum of the individual fluid and membrane resistances:

$$\frac{1}{K_0} = R_0 = R \;+ R \;+ R \qquad (2)$$

where R_0 = overall resistance, min/cm

R = membrane resistance, min/cm

R = blood-side resistance, min/cm

R = dialysate-side resistance, min/cm

RESULTS AND DISCUSSION

The 12 values of the mass transfer coefficients obtained experimentally may be represented as a 3 x 4 matrix as shown in Table 2.

TABLE 2
Experimental Mass Transfer Coefficients

Blood-side flow rate ml/min.	Dialysate-side flow rate, ml/min. 250	400	500	600
150	0.0157	0.0175	0.0159	0.0188
200	0.0168	0.0189	0.0206	0.0215
250	0.0173	0.0195	0.0197	0.0206

The units on the coefficients are cm/min.

An estimation of the membrane resistance may be obtained for cellulosic membranes from the following expression (1):

$$R = \frac{t}{D_{eff}}$$

where t = membrane thickness, cm

D_{eff} = effective diffusivity of solute within the membrane

The effective diffusivity of sodium chloride at 23°C is 2.1×10^{-6} cm²/sec and the thickness of the fiber membrane from Table 1 is 30 microns, thus the membrane resistance is 23.7 min/cm at 23°C.

The mass transfer coefficients presented in Table 2 represent the reciprocal of R_0 as defined in equation (2). By use of the Wilson method the individual fluid film resistances

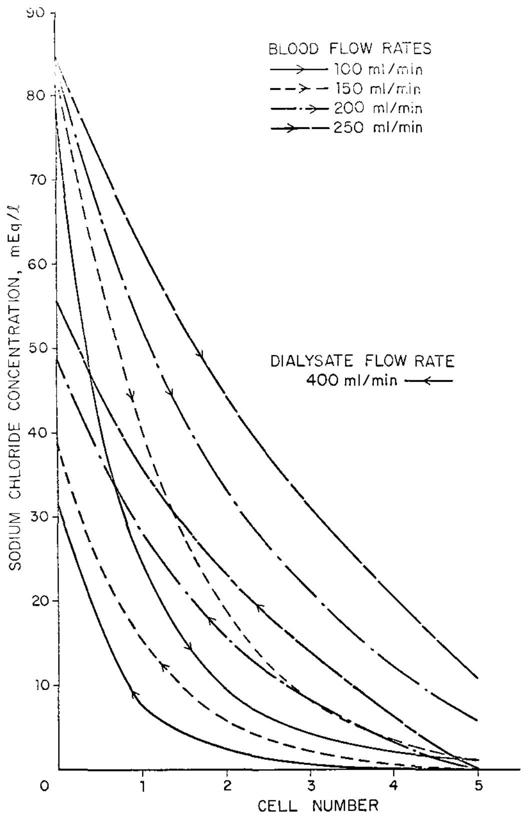


FIGURE 3. LENGTH CONCENTRATION PROFILES FOR HOLLOW FIBER DIALYZERS

could be found. This would require that the fluid velocities on either side of the membrane be increased into the turbulent region.

A knowledge of mass transfer coefficients and a consideration of individual resistances operating within artificial kidneys, such as hollow-fiber dialyzers, can be a great aid in understanding the performance of such devices.

REFERENCE

1. Babb, A. L. and Farrell, P. C.: *Journal of Biomedical Materials Research*, 7, 275 (1973).