Thoughts and Progress

Comparison of Hollow Fiber Dialyzers

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In the tables accompanying this article, all known hollow fiber dialyzers on the market are compared under the headings: "Technical Data", "Performance Data", and "Other Data." Only actual types are included and in some cases values had to be estimated or obtained from secondary sources (a few companies failed to respond to my request for the latest data sheet and will have to accept being listed and compared like this).

The tabulation under "Technical Data" needs little explanation. It may only be mentioned that the surface area given by most manufacturers is the *dry internal* area:

$$A_{di} = 2\, N\, \pi\, r_i\, L_e$$

where: N = *number of fibers*
r_i = dry inner radius of a fiber
L_e = effective length of a fiber.

In reality, however, the true surface area is related to the logarithmic mean radius of the *wet* fiber:

$$A = 2\, N\, \pi\, r_m\, L_e,$$

$$r_m = \frac{r_{wo} - r_{wi}}{\ln \dfrac{r_{wo}}{r_{wi}}} = \frac{h_w}{\ln\left(1 + \dfrac{h_w}{r_{wi}}\right)}$$

where: r_{wo} = wet outer radius
r_{wi} = wet inner radius
h_w = wet wall thickness.

The derivation of this formula is given in the Appendix. Cuprophan fibers swell, when wet, about 10% in the inner radius and about 79% in wall thickness (information from Enka AG). Since little is known about the swelling of other fibers, no true surface areas have been included in the tables. The values of internal diameters and wall thicknesses given are all for dry fibers, except (presumably) for pre-filled dialyzers. This may also hold for blood and dialysate space volumes, which often are given by manufacturers for the dry state (as calculated or as measured with kerosene or some oil, since measurements with water are subject to absorbtion in the fiber walls and liquid loss through slight ultrafiltration.). For wet fibers, the blood space volume then increases by the amount:

$$\Delta V = N\, L_{eff}\, \pi\, (r_{wi}^2 - r_i^2) + N\, L_p\, \pi\, (r_{wip}^2 - r_i^2),$$

where L_p is the length of the fibers inside the potting and r_{wip} the wet inner radius of a fiber in this section. The latter can be estimated to be about $r_o - h_w$, since $r_{ow} = r_o$ here, due to outer fixation—or somewhat less since the swelling is restricted in this part of the dialyzer.

The tabulation under "Performance Data" needs some explanation of the way clearances are recalculated for 1 m^2 area. Ultrafiltration values are easily recalculated through simply dividing by the actual surface area (using stated values, here, although the true area discussed above would have been more appropriate). Clearance values, however, must be recalculated in a somewhat more complicated manner. An approximate but here sufficient formula for the clearance of a hollow fiber dialyzer is :[1-3]

$$Q_{cA} = Q_b Q_d \frac{1 - \exp\left(-\dfrac{A}{R} \cdot \dfrac{Q_d - Q_b}{Q_d Q_b}\right)}{Q_d - Q_b \exp\left(-\dfrac{A}{R} \cdot \dfrac{Q_d - Q_b}{Q_d Q_b}\right)}$$

where: A = surface area in m^2
Q_{cA} = clearance in ml/min at A
Q_b = blood flow in ml/min
Q_d = dialysate flow in ml/min
R = diffusion resistance in $m^2 \cdot$ min/ml
= 10^4 min/cm.

With the same fiber dimensions, and therefore the same R in both cases (neglecting possible differences in dialysate boundary layers in various bundle sizes), the clearance Q_{c1} at $A = 1\ m^2$ and at the same flow rates is then given by:

$$Q_{c1} = Q_b Q_d \frac{1 - E}{Q_d - Q_b E}$$

where

$$E = \left(\frac{Q_d}{Q_b} \cdot \frac{Q_b - Q_{cA}}{Q_d - Q_{cA}}\right)^{1/A}$$

Formulae for clearances at the actual surface and at 1 m^2, with the standard flow values Q_b = 200 ml/min and Q_d = 500 ml/min, are:

$$Q_{cA} = 1000 \frac{1 - \exp(-0.003A/R)}{5 - 2\exp(-0.003\ A/R)}$$

$$Q_{c1} = 1000 \frac{1 - E}{5 - 2E}$$

$$E = \left(\frac{1 - 0.005\ Q_{cA}}{1 - 0.002\ Q_{cA}}\right)^{1/A}$$

If Q_{cA} is measured with an ultrafiltration rate of Q_u, the value so calculated for 1 m^2 corresponds to an ultrafiltration rate of Q_u/A. Clearances are often measured with a certain ultrafiltration, for two reasons: 1) the resulting values are higher and look better in the data sheet; and 2) keeping $Q_u = 0$ during in vitro measurements requires some care (but the corresponding clearance can be determined by means of extrapolation instead). The physically proper characterization of a dialyzer is, however, to state Q_{cA} at $Q_u = 0$, and in the author's opinion, this should be adopted as standard, since only this value is a measure of the diffusive properties of a dialyzer—with ultrafiltration, there is a mixed diffusive and convective transport. A complete characterization should therefore also include a value of clearance increase per unit of ultrafiltration rate, but this is rarely found.

Values of Q_{cA} are normally given in the standard situation of $Q_d = 500$ ml/min and $Q_b = 200$ ml/min. If other flow rates are used, Q_{cAs} of the standard situation can be calculated as:

$$Q_{cAs} = 1000 \frac{1 - B^{0.003}}{5 - B^{0.003}}$$

where

$$B = \left(\frac{Q_d}{Q_b} \frac{Q_b - Q_{cA}}{Q_d - Q_{cA}}\right)^{Q_d Q_b/(Q_d - Q_b)}$$

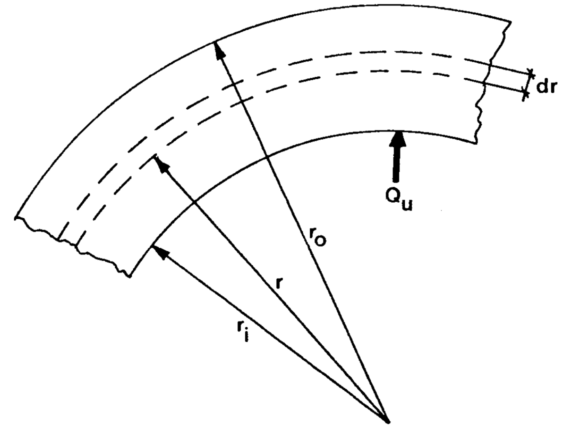
As is seen from the tables, clearance and ultrafiltration values per square meter vary a lot. The performance of a dialyzer is therefore poorly characterized through surface area alone—in fact, dialyzers of different areas can have similar performances. Therefore, the present emphasis on surface area should be abandoned as less relevant and a dialyzer should instead be chosen according to ultrafiltration and clearance. This choice would be easier in the clinic if such values were given on the label.

References

1. KAPLAN S, MCNABB A. Input-output relations for a countercurrent dialyzer by the method of invariant imbedding. Mathematical Biosci. 3:289, 1968.
2. SIGDELL JE, A mathematical theory for the capillary artificial kidney. Hippokrates Publishers, Stuttgart, 1974.
3. KLEIN E, HOLLAND F, LEBOEUF A, DONNAUD A, SMITH JK. Transport and mechanical properties of hemodialysis hollow fibers. J Mem Sci 1:371, 1976. (This work contains an error in the derivation of clearance formulae.)

Appendix

Consider ultrafiltration through a fiber wall, as shown in the Figure. Due to the continuity, the flow rate Q_u through the wall is the same at every value of the radius r, $r_i \le r \le r_o$. For a homogeneous material,



the pressure drop over the annular section from r to $r + dr$ amounts to

$$dp = \frac{kQ_u}{2\pi r} dr$$

where k is a constant. Integrated, this yields the full pressure drop from inside to outside:

$$\Delta p = \frac{kQ_u}{2\pi} \ln \frac{r_o}{r_i}.$$

If we put this as

$$\Delta p = \frac{kQ_u}{2\pi r_m} (r_o - r_i)$$

defining a mean radius r_m, we get:

$$r_m = \frac{r_o - r_i}{\ln \frac{r_o}{r_i}}$$

The same results from a study of diffusion transport.

This means that the fiber has the same radial transport resistance per unit length as the resistance of a flat membrane of the same material having the thickness $r_o - r_i$ and with the width $2\pi r_m$, which then has a surface area per unit length of $2\pi r_m$.

Example: Cuprophan fiber C1 (Enka AG):

$r_i = 0.1$ mm, $r_o = 0.111$ mm, $h = 0.011$ mm

$r_{iw} = 0.11$ mm, $r_{ow} = 0.13$ mm, $h_w = 0.020$ mm

A dialyzer with this fiber, having 1 m^2 dry internal surface area, has 1.1 m^2 wet internal surface area and 1.2 m^2 true wet surface area. The true dry surface area is 1.05 m^2.

An exact calculation of the true wet surface area should in principle also consider the change in the effective length when the fiber is wetted. However, this change is negligible—at least for Cuprophan (about 0.5%). Recent information indicates that cuprammonium rayon fibers swell 7.5% in internal diameter and 20% in wall thickness.

This text was published in *Artificial Organs* Vol. 5, No. 4, 1981 as an introduction to a lengthy set of tables comparing hollow-fiber dialyzers on the market in 1981. Since the tables are no more actual, they have been left out, but the discussion in this introduction may be of interest to persons performing such comparisons to day. The address stated in the beginning is no more valid.

One correction has been introduced in a formula.