Journal of Membrane Science 501 (2016) 123–133

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Simulation and experimental study on the effect of channeling flows on the transport of toxins in hemodialyzers

Weili Li [a,b,1], Jing Liu [a,b,1], Liqun He [c], Juanjuan Liu [a,b], Sijie Sun [d], Zhongping Huang [e], Xin M. Liang [a,b], Dayong Gao [f,*], Weiping Ding [a,b,g,**]

[a] Center for Biomedical Engineering, University of Science and Technology of China, Hefei, Anhui 230027, China
[b] Department of Electronic Science and Technology, University of Science and Technology of China, Hefei, Anhui 230027, China
[c] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, Anhui 230027, China
[d] Department of Laboratory Medicine, University of Washington, Seattle, WA 98195, USA
[e] Department of Biomedical Engineering, Widener University, Chester, PA 19013, USA
[f] Department of Mechanical Engineering, University of Washington, Seattle, WA 98195, USA
[g] Anhui Provincial Engineering Technology Research Center for Biopreservation and Artificial Organs, Hefei, Anhui 230027, China

ARTICLE INFO

Article history:
Received 4 June 2015
Received in revised form
21 November 2015
Accepted 23 November 2015
Available online 27 November 2015

Keywords:
Channeling flow
Mass transport
Hemodialyzer
Hollow fiber membrane
Clearance

ABSTRACT

Channeling flows are common phenomena that exist on the dialysate side in hemodialyzers, and they significantly affect the performance of hemodialyzers. Today, the effect of channeling flows on the clearance of uremic toxins has been studied only experimentally and not theoretically because of its complexity. In this paper, we for the first time introduced a method to mimic channeling flows and, thus, quantitatively investigated the impact of channeling flows on the transport of toxins. The experimental results show that the effect of channeling flows is more significant when the dialysate flow rate is low. The theoretical results show that the flow velocity and toxin concentration fields under channeling flows are qualitatively consistent with the ones published in the literature. Channeling flows induced by the non-uniformity in the hollow fiber packing density can significantly affect the toxin concentration profiles on both dialysate and blood sides and, thus, decrease the clearance of toxins. The effect of channeling flows on the toxin transport is more significant when the fiber packing density is low. The method developed here can be embedded into various theoretical models to match more closely the calculated toxin clearance to reality or to optimize the dialysate flow profiles in hemodialyzers.

1. Introduction

A hemodialyzer, or artificial kidney, is a blood purification device that is mainly designed to remove uremic toxins from patients with kidney failure. The core of a hemodialyzer is a bunch of hollow fibers. Blood passes through the lumen of hollow fibers, while dialysate flows around the outside of hollow fibers countercurrently. In hemodialysis, toxins are transported from blood to dialysate because of diffusion and convection across the semipermeable fiber membrane and are eventually removed with the discarding of dialysate. There are many factors affecting the solute transport of a hollow fiber module [1–3], among which the channeling flow is very important [2–8].

The channeling flow is a dialysate flow phenomenon in which the dialysate preferentially flows through large gaps or low fiber-density regions due to the confining walls of hollow fibers. This phenomenon is mainly caused by two factors: one is the non-uniform distribution of hollow fibers resulting from the defective packing technology [6]; the other is the twist in hollow fibers resulting from the soft fiber property [8]. The occurrence of channeling flows causes a reduction in the clearance of solutes.

In the study on channeling flows, many efforts are made towards the noninvasive detection of channeling flows using MRI [8–12] and CT [13–16]. In this respect, Ronco et al. [5–7] have published many outstanding papers; they not only confirmed the universality of the non-uniform dialysate flow induced by channeling flows but also deeply studied the negative effect of channeling flows on the efficiency of hemodialyzers. Based on non-invasive visualization techniques, some optimizations have also been recently proposed to reduce channeling flows, such as the addition of spacer yarns or filaments between fibers [17,18], the adoption of wavy fibers [19,20], the design of jackets or baffles [20–23], and the application of a constriction ring attached to the

* Corresponding author.
** Corresponding author at: Department of Electronic Science and Technology, University of Science and Technology of China, Hefei, Anhui 230027, China.
E-mail addresses: dayong@u.washington.edu (D. Gao), wpdings@ustc.edu.cn (W. Ding).
[1] These two authors contributed equally to this work.

http://dx.doi.org/10.1016/j.memsci.2015.11.037
0376-7388/

inner wall in the middle of hemodialyzers [6,24].

In the study on channeling flows, although the experimental work is progressing rapidly, the relevant theoretical work has not been reported. In practice, theoretically studying channeling flows is very important as it contributes to obtaining a more accurate toxin clearance of hemodialyzers for making a more effective treatment plan and is conducive to saving time and cost in optimizing the structure of hemodialyzers. Currently, the difficulty of theoretically studying channeling flows is that one has to confront the complicated 3-D flow velocity and solute concentration fields induced by the random distribution and movement of hollow fibers. In this sense, 1-D and 2-D mathematical models in the literature [25–27] are no longer viable despite their advantages of quickly and easily estimating the clearance of toxins. To obtain the 3-D velocity and concentration fields, one might attempt to consider all fibers and their distribution. However, this approach would require the discretization of complex regions and the formulation of a large set of equations, resulting in the requirement for tremendous computational resources. Recently, the porous medium concept has been introduced to study the flows and the transport of toxins in hemodialyzers [26,28]. However, these studies are all based on the assumption that the distribution of the hollow fibers is uniform.

Therefore, in this study, we develop a method to mimic the random distribution induced by the defective packing and the movement of hollow fibers so that channeling flows can be investigated, facilitating the quantitative description of the effect of channeling flows on the transport of toxins from blood to dialysate or the clearance of toxins. The work presented here is of great significance to obtain a more accurate clearance of toxins and optimize the structure of hemodialyzers.

2. Theory

2.1. Method for fiber space distribution modeling

To study channeling flows in hemodialyzers, the space distribution of hollow fibers/the flow channeling should be mimicked in advance. Generally, all fibers are randomly distributed in hemodialyzers. In a simulation, it is easy to arrange fibers randomly. However, it is not easy to describe mathematically the gap induced by the randomness of the fiber distribution in the flow equations. In our previous work [29], we developed a double porous media concept to study blood and dialysate flows in hemodialyzers, which makes it possible to overcome the above difficulty by defining the localized Darcy permeabilities related to the localized porosity/the localized fiber density. Then, the resulting issue is how to calculate the localized permeabilities. One might use the Voronoi Tessellation method [30,31] or the "imaginary free-surface cells" technique [32,33] to describe the subdivision of space between randomly distributed fibers and then obtain the localized permeabilities. However, these methods will cause a rapid increase in the necessary computing resources as a mesh smaller than the subdivision is required. One also might adopt the spatially periodic distribution of hollow fibers to obtain the localized permeabilities, but a proper boundary treatment is required to study the channeling flow near the dialyzer shell. For the work in [31], with a proper boundary treatment, it may be possible to address the near shell condition.

To avoid the complexity of obtaining the localized permeabilities, the method we propose here is as follows (Fig. 1). First, the cross section perpendicular to the flow direction of blood is divided into a certain number of subdomains with relatively uniform areas (a_i, $i = 1, 2, \dots, M$; the subscript i denotes the i^{th} subdomain; a_i is the area of the i^{th} subdomain; M is the number of

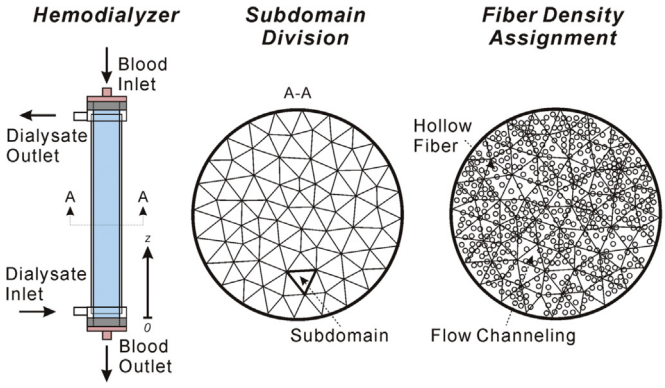

Fig. 1. Schematic of the fiber space distribution modeling.

subdomains). Second, a series of fiber densities (λ_i, $i = 1, 2, \dots, M$; λ_i is defined as the localized fiber density), obeying a Gaussian distribution, are assigned to subdomains (the localized fiber number in Fig. 1 is schematic and represents the localized fiber density). Third, the cross section is discretized into high-quality finite element meshes. By randomly assigning fiber densities to subdomains, the random space distribution of fibers is simulated indirectly. Thus, the flow channeling can be mimicked and then the velocity field and the toxin concentration fields under channeling flows can be theoretically investigated.

Based on this method, the dialyzer cross section area (A), the average number of fibers ($\overline{\lambda}$), the average packing density of fibers ($\overline{\phi}$, PDF), the localized packing density of fibers (ϕ_i), the localized porosity on the blood side ($\varepsilon_{b,i}$), and the localized porosity on the dialysate side ($\varepsilon_{d,i}$) can be described as

$$A = \sum_{i=1}^{M} a_i = \pi r_{hd}^2 \tag{1}$$

$$\overline{\lambda} = N/A = \sum_{i=1}^{M} \lambda_i a_i / \sum_{i=1}^{M} a_i \tag{2}$$

$$\overline{\phi} = N\pi r_{ho}^2/A = \pi r_{ho}^2 \sum_{i=1}^{M} \lambda_i a_i / \sum_{i=1}^{M} a_i \tag{3}$$

$$\phi_i = \lambda_i \pi r_{ho}^2 \tag{4}$$

$$\varepsilon_{b,i} = \lambda_i \pi r_{hi}^2 \tag{5}$$

$$\varepsilon_{d,i} = 1 - \lambda_i \pi r_{ho}^2 = 1 - \phi_i \tag{6}$$

where, r_{ho} is the outer radius of hollow fibers, r_{hi} is the inner radius of hollow fibers, r_{hd} is the inner radius of the dialyzer shell, N is the total number of fibers, and subscripts b and d denotes blood and dialysate sides, respectively.

Here, it should be noted that ϕ_i reaches a maximum of 0.907 when the fibers are arranged very tightly under a regular triangle array mode; as a result, the standard deviation (STD) of the Gaussian distribution needs to be set properly so that 99.9% of ϕ_i values is no more than the maximum. When the previous steps are finished, the localized Darcy permeabilities on both blood and dialysate sides can be calculated by the following equations according to the literature [29,34,35]: