ABSTRACT

Hemodialysis is the most widely used Renal Replacement Therapy for the treatment of failed kidneys. In the event of kidney failure, the unwanted substances that accumulate in the blood needs to be excreted. Increased acid levels and abnormal levels of Urea, Creatinine, Glucose, Endothelin, β2-Microglobulin and Complement Factor D indicate the malfunctioning of the kidneys. Serum urea and creatinine are the two main biomarkers that assess the performance of the human kidneys. The hemodialyser known as the “Artificial kidney” is the replacement of the natural kidney and is the heart of the hemodialyser machine. The dialyser module comprises of thousands of hollow fibers which act as the semipermeable membrane to filter the impurities from the blood. The performance of the dialyser is dictated by the membrane design and chemical composition. One of the main challenges in hemodialyser membrane design is to enhance the clearance rate of solutes. The main objective of this thesis is to investigate the factors affecting the performance of the hemodialyser and to enhance its filtering efficiency. Morphological studies were performed to understand the structural details of the hollow fiber membrane, as the structure decides the performance of the membrane. Computer aided modeling and simulation techniques help to analyse the critical parameters that affect the dialysis process and identify the means to enhance the filtering efficiency.

In order to study the structural details of the hemodialyser, a bench mark dialyser module F6HPS was purchased from PSG Hospital, Coimbatore. The fibers from the dialyser module were physically tested using various advanced characterization techniques viz. (i) Field Emissive Scanning Electron Microscope (FESEM) (ii) Atomic Force Microscope (AFM) and (iii) Tensile test. FESEM micrographs revealed the morphology and cross sectional details of the fibers. Image analysis was implemented to calculate

the pore diameters of the outer surface quantitatively. The morphological operations and Euclidean distance transform were used to quantify the pore diameter of the pores and porosity of the outer surface. As the FESEM could not probe the details of the inner surface of the hemodialyser membrane, AFM technique was used. AFM revealed the pore morphology of both the inner and the outer surface of the membrane and a measure of the surface roughness, which is an essential factor in the membrane design. It is evident, that the outer surface pores can be imaged with ease as the pore diameters were in microns, while the inner surface pores required sophisticated imaging technique since the dimensions were in nanometers.The mechanical strength of the fibers were tested in a tensile tester to find the load bearing ability of the membrane. Thus a comprehensive analysis was performed to study the structural details of the hemodialyser membrane. The wall thickness, inner diameter, porosity, Young's modulus and Poisson's ratio were the main parameters obtained from the study and were fed as input parameters for the developed models.

A two dimensional axi-symmetric model of the membrane was developed to simulate the dialysis process, in order to determine the important parameters for getting better clearance of toxin molecules and therefore to change those parameters to improve the performance of the dialysis. Blood flow containing Urea, Glucose, Endothelin, β2-Microglobulin, Complement Factor D and Albumin was introduced. The influence of varying the blood flow rate, dialysate flow rate,thickness, length, porosity and the number of fibers on the clearance rate of solutes has been simulated. It has been inferred, that the increase in the blood flow rate, the dialysate flow rate and the number of fibers increased the clearance rate of solutes whereas the increase in membrane wall thickness, decreased the clearance rate of the solutes. The porosity of the membrane layers were varied and simulated. The results show that, the dialyser was able to achieve good clearance when the porosity of all the three layers were the same. This study strongly suggests that, the porosity of the membrane across the entire cross section of the membrane should be equal and the membrane wall thickness have to be minimal to achieve superior clearance rate of solutes.

Further, three dimensional models of the hemodialyser membrane were developed to study the impact of varying the fiber's orientation (shape). The dialyser's fibers are oriented in either straight or crimped configurations, hence straight and crimped models were developed. The effect of crimping the fibers alters the clearance rate of the solutes, hence comparative studies were performed on the transport characteristics of urea in straight and crimped models. In the crimped fibers, the clearance is affected by two important parameters namely crimp amplitude and crimp frequency, which were varied and simulated. It has been inferred that increasing the crimp amplitude and frequency increased the clearance rate of the solutes. The crimped fiber model exhibited good clearance rate when compared to the straight fiber model.

A modification in the membrane design was introduced by corrugating the inner layer of the membrane in both the straight and crimped fiber models. The simulations were performed and the results of the study showed that the clearance rate of urea for crimped - corrugated model was significantly high when compared to the non corrugated- crimped and non corrugated-straight fiber models. This study is considered as a novel contribution of the research work because the existing hemodialysers have not incorporated this design criterion.

It is highly essential to analyse the mechanical stability of the fibers since they are being subjected to continuous blood flow for several hours. Real time experimental studies cannot predict the mechanical behavior of the fibers during dialysis. In this research work, the Fluid Structure Interaction (FSI) model, which couples the flow properties with the structural mechanics, is implemented to study the interaction of blood flow with the structure of the hollow fiber under various flow conditions. The density and viscosity of blood was fed as input parameters for the fluid part and the Young's modulus and Poisson's ratio was fed as input parameters for the membrane. The yield strength of the fibers can be predicted by computing the von Mises criterion, under varying flow conditions to analyse the stress distribution in the walls of straight and crimped fibers with and without corrugations. The results showed that in non-corrugated model, the crimped fibers experience less stress when compared to the straight fibers. In corrugated model, the stress experienced by crimped fibers is less compared to the straight fibers when the wall thickness was between 20 to 40μm, but when it was increased above 40μm, the stress distribution in crimped fibers increased. Therefore, the Crimped-corrugated fiber model would have better mechanical stability if the wall thickness was optimized.

In order to analyse the performance of the dialyser membrane based on the chemical composition, novel asymmetric polysulfone (PSF) membranes were prepared from Chitosan/Chitosan nanoparticles and PSF blended with Polyethylene glycol (PEG) and Polyvinylpyrrolidone (PVP) through immersion precipitation technique. The variation in pore size and surface morphology of the prepared membranes were studied by FESEM and contact angle measuring instrument. The contact angle measurements demonstrated that hydrophilicity of the PSF membranes was significantly enhanced by the addition of Chitosan/Chitosan nanoparticles than PVP-PEG and the improved pore size were confirmed through FESEM studies. These membranes with modified surface and better pore morphologies will be suitable for biomedical applications like hemodialysis.

Hence, this thesis has investigated the performance of the hemodialyser membrane through various techniques and suggests certain design considerations to enhance its filtering efficiency.