Kinetic modeling of fluid and solute transport in peritoneal dialysis

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Abstract—Mathematical models for fluid and solute transport during peritoneal dialysis are described. A model for the transport of the so-called volume marker enables the correct estimation of the kinetics of the intraperitoneal dialysate volume as well as the rate of peritoneal fluid absorption. On the basis of these estimations, the solute transport components (diffusion, convective solute transport with ultrafiltrate and peritoneal solute absorption) may be separated within the net solute transport using a modified version of the Babb–Randerson–Farrell (BRF) model. The diffusive mass transport coefficient and sieving coefficient are given by the model. A simplified method for the estimation of the diffusive mass transport coefficient during the so-called isovolemia period is also described and compared to the BRF modeling. The three-pore model and the distributed model, which describe the structure–function relationship for the peritoneum, are also addressed.

Key words: Peritoneal dialysis; kinetic model; diffusion; convective transport; peritoneal membrane.

1. INTRODUCTION

Peritoneal dialysis is based on transport of solutes and water from blood flowing in small blood vessels distributed in the peritoneal tissue to dialysis fluid (dialysate) in the peritoneal cavity. In contrast to the rather simple transport of solutes and water across a permselective membrane in a hemodialyzer, transport across the peritoneal barrier is much more complicated [1]. Peritoneal tissue is heterogeneous and the surface of this tissue is not smooth but contains pockets with poorly mixed space which hinders the transport of solutes between blood and dialysate. Additionally, there is a lymphatic transport of solutes and fluid which is different in different parts of the peritoneal tissue.

This brief description of solutes and fluid transport in peritoneal dialysis suggests that any detailed mathematical model of transport phenomena should be very
complicated. In fact, although several models have been proposed, such as the three-pore model [2], which takes into account the physiology of transport across blood capillary walls, or the distributed model, which takes into account the distribution of blood capillaries in the peritoneal tissue [3], a detailed mathematical model of solutes and fluid transport has not been constructed yet.

In spite of those difficulties, simplified models were formulated, which have proven to be useful in the evaluation of clinical studies as well as animal experiments concerning peritoneal dialysis.

2. MEASUREMENT OF DIALYSATE VOLUME

Measurement of fluid volume in a container of unknown geometry can be done by infusion of a small amount of fluid containing a known amount of a marker, whose concentration can be measured even if it is very diluted. The volume marker is usually a substance of high molecular weight (e.g. albumin) labeled with a radioactive element (e.g. iodine, $^{131}$I). After instillation of a volume of fluid a sample is taken and the measured volume can be calculated from the dilution of the volume marker. This method is based on the assumption that the volume marker is not absorbed on the surface of the container and that it does not leak from the container. Both of these phenomena exist in peritoneal dialysis. Marker absorption on the surface of the peritoneal cavity can be, at least partly, prevented by addition to the solution of the volume marker (if the volume marker is a labeled substance, e.g. labeled albumin) in a substantial amount of the non-labeled substance (e.g. albumin). The investigation using experimental dialysis in rats has shown that the absorption of albumin on the surface of the peritoneum is rather small and amounts to 4% of the amount of infused marker [4].

The transport of the volume marker from dialysate consists of two transport processes: diffusion and convection. The convective transport consists of the direct lymphatic transport from dialysate to blood and of the fluid absorption to the tissue caused by the hydrostatic pressure in the peritoneal cavity [5].

It is important to note that the diffusive as well as convective flows of the marker are linearly dependent on the marker concentration in the peritoneal cavity. The diffusive transport of the marker to the peritoneal tissue can be substantially limited by the selection of the marker having high molecular weight, because diffusive transport is slower for high molecular weight molecules. For this reason, proteins of a rather high molecular weight, such as albumin or haemoglobin, as well as dextrans of 70 000–2 000 000 Da have been applied as peritoneal volume markers. A review of peritoneal volume markers applied in clinical and experimental studies is presented in [6].

Large molecules and even cells are removed from the peritoneal cavity by lymphatic transport, and therefore this transport cannot be eliminated by the selection of an appropriate volume marker. However, the lymphatic transport can be accounted for and its magnitude can be evaluated using a simple mathematical model.