Kidney International, Vol. 44 (1993), pp. 700–707

Water transport model during CAPD: Determination of parameters

TAKASHI HORIUCHI, YOKO TADA, YUSUKE KUWAHARA, YUJI OHTA, and TAKEYOSHI DOHI

Division of Applied Life Science, Graduate School of University of East Asia, Yamaguchi, and Department of Precision Machinery Engineering, The University of Tokyo, Tokyo, Japan

Water transport model during CAPD: Determination of parameters. To minimize the total amount of glucose required for removing the same volume of water as a bolus, a continuous infusion of glucose during CAPD was proposed and studied. Both a computer simulation of water transport through the peritoneal membrane and *in vivo* assessment with rats were carried out to evaluate the feasibility of the newly proposed mathematical model in which lymphatic drainage of dialysate from the peritoneal cavity to lymphatic system was considered in addition to conventional water transport. Mass transport area coefficients (KA) of 0.041 to 0.063 ml/min/100 g body wt and 0.045 to 0.066 ml/min/100 g body wt were measured for glucose and urea during CAPD with male Wistar rats. Hydraulic conductivity of peritoneal membrane (Lc) was 7.9×10^{-5} to 1.5×10^{-4} ml/min/mm Hg/100 g body wt, which was calculated by a linear relationship between volume and osmotic pressure. Simulated water transport model using determined parameters indicated that the ratio of lymphatic transport to convective transport would be changeable in CAPD with glucose infusion at varying infusion rates, while up to 16% of the glucose uptake could be reduced compared with that of the common CAPD at the same dwell time.

Continuous ambulatory peritoneal dialysis (CAPD) has been established as a modality of treatment for end-stage renal disease. In the common CAPD technique, hypertonic dialysates including 1.5% to 4.25% of glucose concentration are commonly used to remove an excess amount of water from both intra- and extracellular spaces in the peritoneal cavity. However, hyperglycemia and obesity occur in long-term CAPD due to continuous usage of high dosages of glucose [1, 2]. Furthermore, it may be one of the causes of a lack of appetite for some patients with less glycolytic function, particularly in the elderly. Also, exposure of peritoneal membrane to hypertonic solution may cause deterioration of its hydraulic conductivity and solute transport properties. As can be seen in a typical profile of dialysate volume changes during CAPD, volume drastically increases immediately after injection of dialysate, and then gradually decreases following the peak period (or the isovolemic period). This observation has been rationalized as an overall change in concentration gradient of osmotic substances across the peritoneal membrane [3–5]. Therefore, if osmotic pressure gradient across the peritoneal membrane is maintained, intraperitoneal dialysate volume constantly increases, and thus we would expect a higher efficiency of water removal in a minimized glucose dosage, which is preferable to reduce complications associated with use of hypertonic dialysate.

Although use of a mathematical model for water and solute transports is recommended to study to improve the efficacy of CAPD and develop new therapeutic modality, the conventional water transport model based on only diffusive and convective transports cannot be representative of consecutive water transport profile in a wide variety of clinical cases. As one reason, a significant role of lymphatic flow has been considered to be the intraperitoneal water and solute transport [6–13]. However, there still exists uncertainty of the quantitative contribution of lymphatic flow in the intraperitoneal water and solute transport because of difficulties in measurement of lymphatic flow and other parameters used in the mathematical model.

In this paper, a kinetic model of intraperitoneal solute and water transport was proposed, associating a new method to estimate lymphatic flow and hydraulic conductivity of the peritoneal membrane. In addition, to evaluate the feasibility of this model, a simulated model was computed and compared to *ex vivo* experiments.

Methods

Mass transport theory

Figure 1 shows a schematic diagram of an intraperitoneal mass transport model. A two compartment model, separated by the peritoneal membrane into the body fluid compartment and the intraperitoneal dialysate compartment, was employed. The body fluid space was simplified as one compartment, although it consists of both the intracellular and the extracellular spaces, and the intravascular space. Lymphatic flow from the peritoneal cavity into the lymph duct was included in the model.

There are three potential ways of mass transport across the peritoneal cavity: diffusive transport by the solute concentration gradient, convective transport accompanied by ultrafiltration across the peritoneal membrane, and lymphatic transport from the peritoneal cavity to lymphatic channels. Based on these transport mechanisms, the following equations of mass transport across the peritoneal membrane were formulated:

$$\frac{d}{dt}(V_d C_d) = KA(C_d - C_b) + (1 - \sigma)J_{vb}\bar{C} - J_{vl}Cd \qquad (1)$$

Received for publication February 19, 1993
and in revised form May 26, 1993
Accepted for publication May 27, 1993

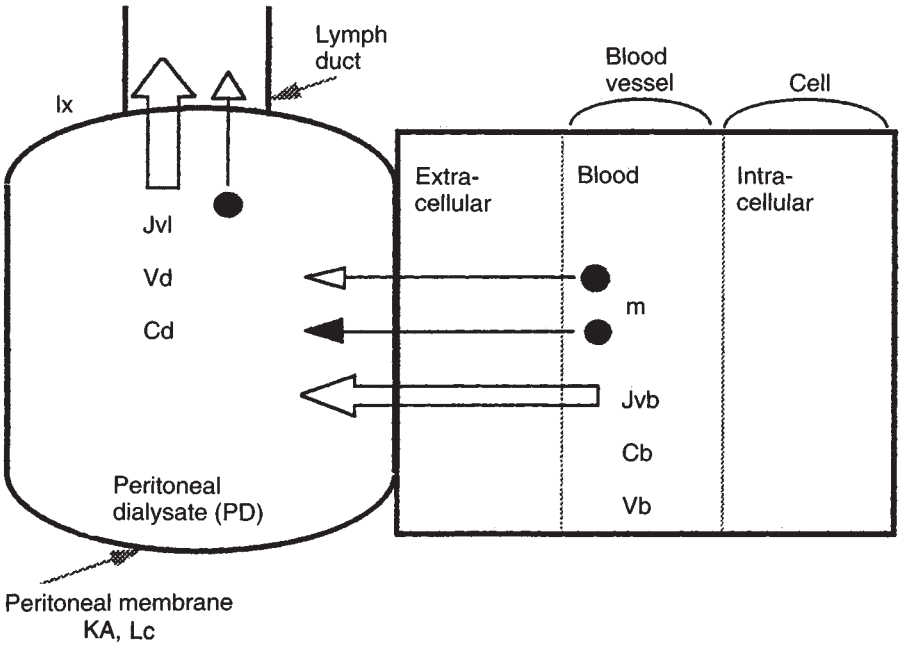

Fig. 1. *Schematic diagram of mass and water transport in CAPD.* Abbreviations are: KA, mass transport area coefficient; Lc, hydraulic conductivity; C, solute concentration; V, volume; b, d, blood and dialysate; m, mass transport. Symbols are: ←, solute flux by diffusive flow; ⇐, solute flux by convective flow; ◁, water flux.

$$J_{vb} = Lc(\Delta p - \Sigma\sigma_i\pi_i - OP) \quad (2)$$

$$J_{vl} = l \times \frac{V_d}{b_w} \quad (3)$$

where the terms are defined in the Appendix.

In equation (1), changes of mass in the peritoneal dialysate per time were balanced by a summation of the diffusive transport term (first term), the convective transport term (second term) and the lymphatic transport term (third term). Diffusive transport can be expressed as overall mass-area coefficient of solute multiplied by concentration gradient of solute across the peritoneal membrane. In the convective solute transport term (second term), J_{vb}, s and $\bar{C}$ are the ultrafiltration rate, Staverman's reflection coefficient, and solute concentration in the membrane, respectively. It was assumed that there was no selectivity among solutes having an osmotic role in solute transport by lymphatic drainage, and its reflection coefficients in the lymphatic term were null [14]. We hypothesized that lymphatic flow rate was a function of intraperitoneal pressure which was supposed to be determined by intraperitoneal dialysate volume. Finally, the lymphatic absorption rate, J_{vl}, is expressed as a linear function of dialysate volume per body weight. The parameter, lx, expressing the lymphatic drainage rate, is referred to as the lymphatic absorption coefficient.

Determination of parameters

As noted in equations (1) through (3), several parameters must be determined to compute consecutive mass and water balance. Mass transport area coefficients (KA) for glucose and urea-N were determined by the Lindholm's isovolemic method [15–17]. Both hydraulic conductivity of the peritoneal membrane and the relationship between lymphatic flow and peritoneal dialysate volume were determined by our own methods.

Male Wistar rats 12-weeks-old were used in this study.

Table 1. Parameters used in simulation (rat)

KA-glucose	0.041 ml/min/100 g body wt
KA-urea	0.045 ml/min/100 g body wt
KA-Na	0.1 ml/min/100 g body wt
σ-glucose	0.3[a]
σ-urea	0.2[a]
σ-Na	0.4[b]
Lc	7.9×10^{-5} ml/min/mm Hg/100 g body wt
lx	1.0×10^{-4} kg/min/100 g body wt

[a] Referred from [25]
[b] Referred from [17, 24]

Mass transport area coefficient (KA). KA was determined during the isovolemic period which is defined as the pseudo-plateau period following a maximum volume change of the peritoneal dialysate [15–17]. In the isovolemic period, contributions of convective term and lymphatic term are negligible since the change of the volume is small. Then equation (1) is approximated as follows.

$$V_d\frac{dC_d}{dt} = KA(C_b - C_d) \quad (4)$$

When the function of the kidney and other organs is constant during the isovolemic period, concentrations of glucose and urea in the body fluid (Cb) can be assumed to be constant [6, 7]. Then equation (4) becomes:

$$KA = -\frac{V_d}{t_2 - t_1} \cdot \ln\frac{C_d(t_2) - C_b}{C_d(t_1) - C_b} \quad (5)$$

Prior to KA measurement, isovolemic periods were determined with peritoneal dialysate containing 2% glucose. Experiments were carried out using Wistar rats with body weights of 405.6 ± 37.1 g (Ave ± SD). Peritoneal dialysis was performed on

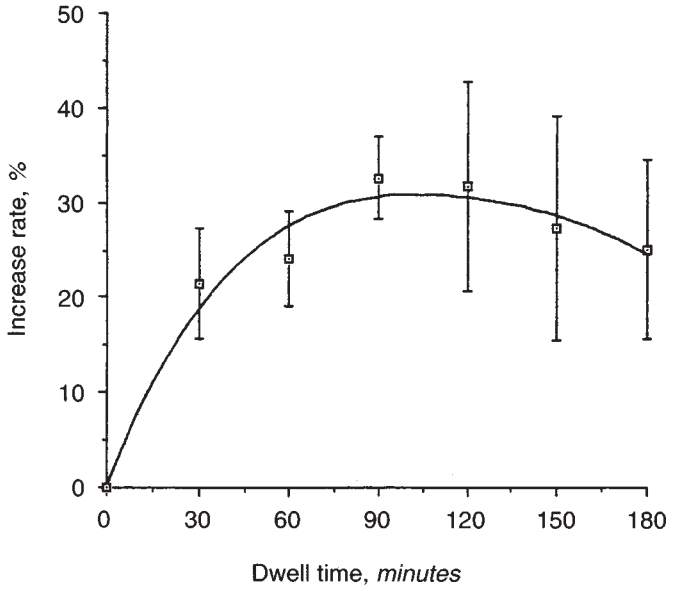

Fig. 2. *Percent of changes in peritoneal dialysate volume as a function of dwell time.*

each of five rats with different dwell time ranging from 30 to 180 minutes (t = 30, 60, 90, 120, 150 and 180 min). At the end of each dwell time, dialysate was drained by a syringe and then residual water was wiped out completely by sanitary cotton and weighed. The drainage volume was determined gravimetrically, and normalized by the injected volume as percent of change.

To calculate KAs of glucose and urea, both 0.2 ml blood and dialysate samples were taken from the femoral veins and the peritoneal cavity of 10 male Wistar rats (average weight 409.6 ± 47.5 g) at time t_1 and t_2 during the isovolemic period, which were pre-determined by the experiment mentioned above. Dialysate was prepared by adding glucose and urea with a final concentration of 2 wt% and 100 mg/dl (Urea-N) to Ringers solution. Initial injection volume of dialysate was 40 ml/kg body wt.

Hydraulic conductivity of the peritoneal membrane. Hydraulic conductivity, Lc, represents the intrinsic parameter of ultrafiltration per a given time across the peritoneal membrane. Ultrafiltration rate, J_{vb}, which is water transport from blood to intraperitoneal dialysate, is assumed as the sum of the derivative of intraperitoneal dialysate volume $(\frac{\Delta V}{\Delta t})$ and drainage rate to lymphatic system (J_{vl}).

$$J_{vb} = \frac{\Delta V}{\Delta t} + J_{vl} \tag{6}$$

J_{vb} is equated as Lc times the transperitoneal pressure difference, which is conventionally represented by a static pressure Δp, osmotic pressure $\Sigma\sigma\Delta\pi$ and oncotic pressure OP as shown in equation (2).

When dialysates with different concentration of glucose are used, the following set of equations is obtained at time t_1 and t_2 from equations (2) and (6) in a similar formulation as reported by Rippe, Perry and Granger [18].

$$Lc(\Delta p_1 - \Sigma\sigma\Delta\pi_1 - OP) = \frac{\Delta V_1}{\Delta t} + J_{vl1} \tag{7}$$

$$Lc(\Delta p_2 - \Sigma\sigma\Delta\pi_2 - OP) = \frac{\Delta V_2}{\Delta t} + J_{vl2} \tag{8}$$

If time interval is short enough, it can be assumed that $\Delta p_1 = \Delta p_2$ and $Jvl_1 = Jvl_2$. Lc is represented as follows from equations (7) and (8).

$$Lc = \frac{\Delta V_1 - \Delta V_2}{\Sigma\sigma\Delta\pi_1 - \Sigma\sigma\Delta\pi_2} \cdot \frac{1}{\Delta t} \tag{9}$$

Osmotic pressure difference can be calculated from glucose concentrations alone when differences in concentration of the other solutes are negligible between the dialysate and blood.

$$\Sigma\sigma\Delta\pi = \sigma RT(C_d - C_b) \tag{10}$$

If glucose concentration in blood is constant then equation (9) is rewritten as

$$Lc = \frac{\Delta V_1 - \Delta V_2}{\sigma RT(C_{d1} - C_{d2})} \frac{1}{\Delta t} \tag{11}$$

Hence, Lc is calculated from change in dialysate volume and glucose concentration between t_1 and t_2.

Experiments were carried out using fifteen Wistar rats with body weight of 407.9 ± 32.4 g. Concentrations of urea N and electrolytes in dialysate were adjusted to normal blood level while glucose concentrations of dialysate were varied to 1.0%, 2.0% and 3.0%. Peritoneal dialysis was performed for 30 minutes. Samples of dialysate and blood were taken by 0.2 ml at 0, 15 and 30 minutes. Volume of dialysate at the end of the dwell time was measured by the same method used in determination of the isovolemic period. To exclude the effect of hydrostatic pressure, the end of peritoneal catheter was opened to atmosphere by attaching an air filter.

Relation between dialysate volume and intraperitoneal pressure. It was assumed that the lymphatic absorption rate was proportional to the intraperitoneal pressure [6, 19]. To formulate lymphatic flow as a function of intraperitoneal pressure, the relationship between dialysate volume and intraperitoneal pressure was measured by the following method.

Prior to measurement of intraperitoneal pressure as a function of volume, pressure-volume characteristics of the thin flexible latex bags were measured using a water manometer outside the body (P_{out}). Then each thin flexible latex bag was placed in the peritoneal cavity of five Wistar rats with an average body weight of 386 ± 54.6 g. Water was infused in 5 ml increments into the bag till total volume reached 50 ml. The abdomen was massaged by hands so that the flexible water pouch was deformed isobarometically in the cavity. Pressure (P_{in}) was measured at every 5 ml injection by a water manometer connected to the peritoneal catheter. This procedure was repeated three times on each rat and averaged. Net pressure was calculated by subtracting P_{out} from P_{in}.

Evaluation of the mass transport model

To evaluate the mass transport model proposed in this study, *ex vivo* experiments using rats were carried out. Peritoneal

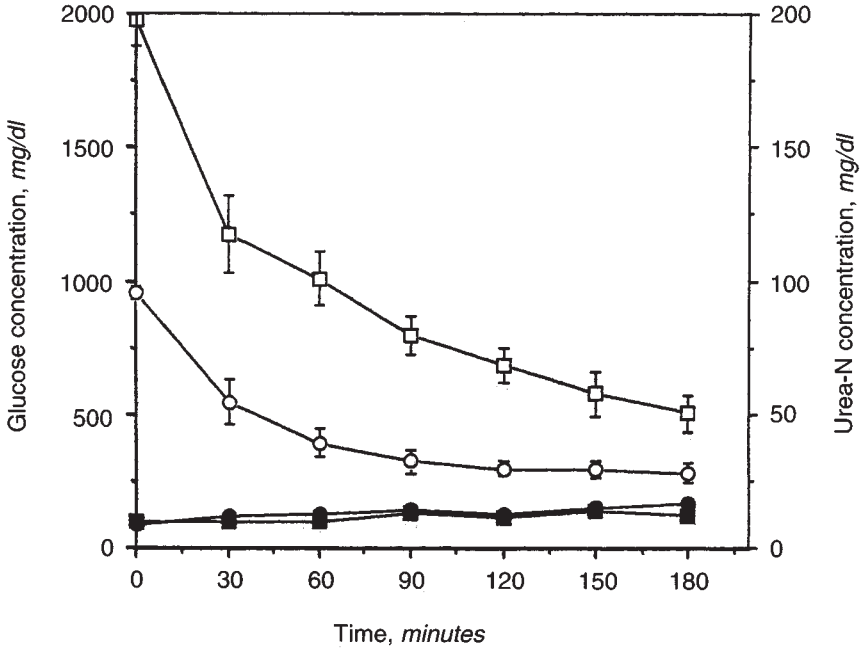

Fig. 3. *Changes in glucose and urea N concentrations in dialysate and blood.* Symbols are: (○) D-urea N; (□) D-glucose; (●) BUN; (■) B-glucose.

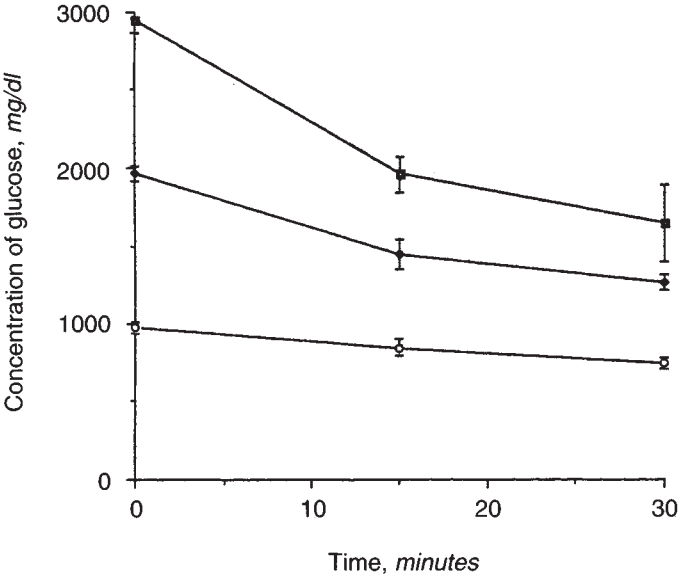

Fig. 4. *Changes in glucose concentration in CAPD at varying initial glucose dosages.* Symbols are: (○) 1%; (◆) 2%; (□) 3%.

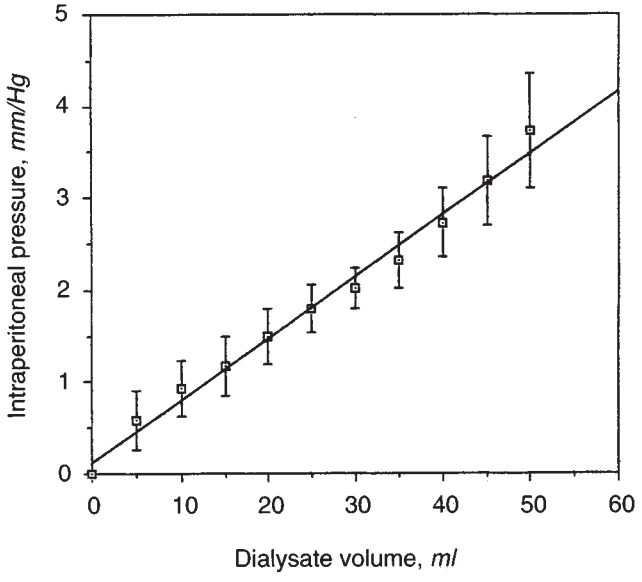

Fig. 5. *Intraperitoneal pressure versus dialysate volume.*

dialyses with continuous glucose infusion were performed for 180 minutes on five Wistar rats with an average body weight of 389.0 ± 29.7 g. The expected removal amount of water was set to 1.1 ml/100 g body wt, which was estimated as the same volume removed by the common CAPD. One hundred microliters of glucose solution (22.5 wt%) was infused into the peritoneal cavity at every 10 minutes. Samples were taken from dialysate at every 30 minutes. Computer simulation of mass transport during peritoneal dialysis was carried out using parameters listed in Table 1 under the same conditions as the *in vivo* experiments. Comparison between measured and simulated values was evaluated for glucose concentrations in dialysate.

Computer simulation of glucose uptake at varying modalities of intake

Using a computer simulation of the proposed mass transport model, various modalities of the glucose intake were evaluated to find the minimized glucose uptake to the body. Parameters used in this simulation are listed in Table 1. Relationships

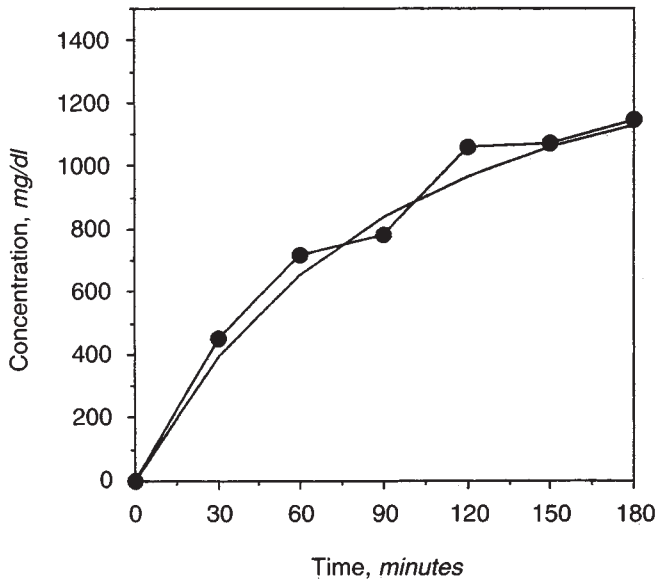

Fig. 6. *Comparison between calculated (—) and measured (-●-) glucose concentration in intraperitoneal dialysate.*

between the initial concentration of glucose uptake and the infusion rate were computed by varying the amount of water removed. Differences in glucose uptake between the bolus injection and continuous infusion were computed at varying glucose concentrations as a function of dwell time.

Results

Estimation of isovolemic time

Figure 2 shows the relation between dwell time and increase rate of dialysate volume on peritoneal dialysis using rats with 2 wt% glucose dialysate. The percent increase of dialysate volume reached the maximum value at 90 minutes. After 90 minutes the volume did not change remarkably, although data were somewhat deviated. From this observation, the time range between 75 and 105 minutes was determined as the isovolemic period, and 32.6% maximum percent increase was used as the percent volume increase of the isovolemic period, shown in the following calculations as V_d.

Calculation of KA

Figure 3 shows changes in concentrations of glucose and urea N in both dialysate and blood during the 180-minute peritoneal dialysis. Blood levels in both solutes were maintained constant. Solute concentrations in dialysate at t_1 (75 min) and t_2 (105 min) were calculated as the arithmetic means of those at 60 and 90 minutes, and at 90 and 120 minutes, respectively. The value at 90 minutes was used for solute concentration in blood (Cb).

From substituting these values into equation (5), the KA of glucose and urea N in rat were calculated as 0.041 to 0.063 and 0.045 to 0.066 ml/min/100 g body wt in the ranges of 1 to 0.7 and 1 to 0.74 of scaling factors, respectively [20].

Calculation of Lc

Percent increase of dialysate volume was measured before the isovolemic period and its value at 30 minutes was linearly correlated to the initial concentration of glucose in dialysate. The percent increases were 4.6%, 15.3% and 25.9% with 1%, 2% and 3% glucose concentration in the dialysate, respectively. Figure 4 shows the concentrations of glucose in dialysate where the initial concentrations were 1%, 2% and 3%. To calculate Lc by equation (11), the percent increases of dialysate and glucose concentrations at 15 minutes were used as the mean values of the first 30 minutes. By substituting these values into equation (11), 7.9×10^{-5} to 1.5×10^{-4} ml/min/mm Hg/100 g body wt of Lc was calculated for male Wistar rats.

Relation between dialysate volume and intraperitoneal pressure

Figure 5 shows the relationship between intraperitoneal pressure and dialysate volume. It shows that the dialysate volume in peritoneal cavity is proportional to the pressure inside of the flexible latex bag within the volume less than 50 ml, which corresponds to approximately 7.5 liters in the common CAPD for human patients. As the latex bag used in experiment was highly elastic, dialysate volume may be directly proportional to intraperitoneal pressure which is mainly dominated by compliance of the abdominal wall. Lymphatic absorption coefficient, lx, was determined as 1.0×10^{-4} to 1.5×10^{-4} kg/min/100 g body wt by curve fitting of equations (1) through (3).

Evaluation of mass transport model

Figure 6 shows a good agreement between glucose concentrations measured in dialysate and those calculated by simulation. These results indicate validity of both the newly proposed mass transport model and measurement of parameters on rats.

Computer simulation of glucose uptake at varying modality of intake

Figure 7 shows the difference of glucose uptake between infusion mode and bolus injection mode. Up to 16% reduction of glucose uptake was estimated in infusion mode while volume of water removal was same. In this simulation volume of water removal ranges between 1 to 4 ml which corresponded to 150 to 600 ml (33 to 133 ml with 0.7 scaling factor) in the common CAPD with a human patient. Generally speaking, the percent of reduction of glucose uptake increases as the dwell time is longer and glucose concentration of bolus injection is higher.

Figure 8 shows relation between initial concentration of glucose versus glucose uptake and infusion rate at varying removal amount of water from 1.0 ml to 4.0 ml. Glucose uptake can be minimized when continuous glucose infusion mode is employed without initial bolus injection.

Discussion

Although it is clinically useful to mathematically simulate mass transport across the peritoneal membrane during CAPD, some uncertainties still exist for the determination of parameters in the equation and the understanding of complicated transport phenomena. Recently it has been pointed out that lymphatic flow may play a significant role of mass and water transport during peritoneal dialysis [6–13]. There are many

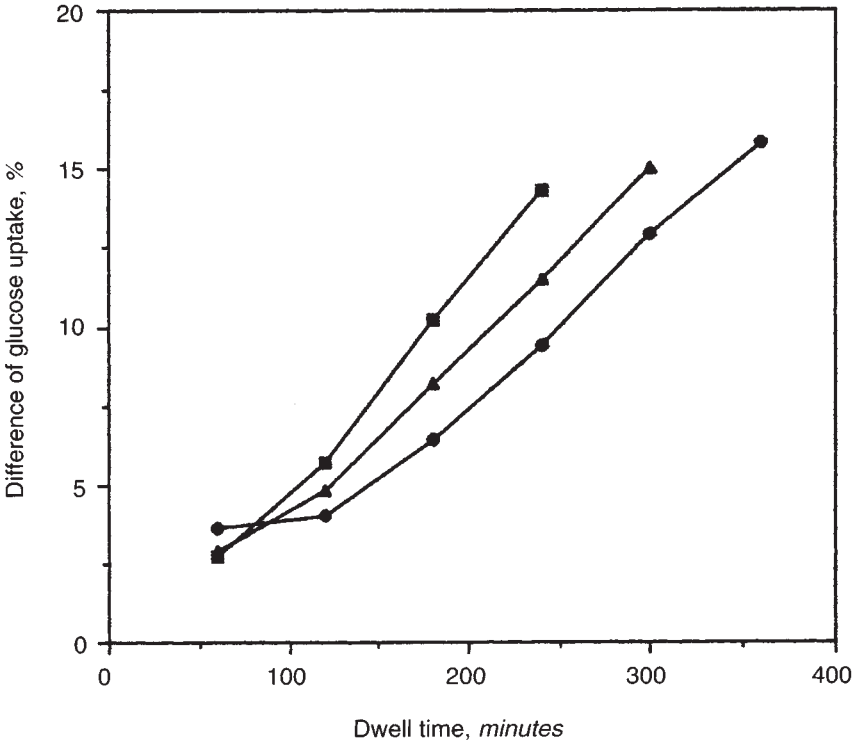

Fig. 7. *Relations between initial concentration of glucose versus glucose uptake and infusion rate at varying removal amounts of water from 1.0 ml to 2.5 ml (simulation model).* Symbols are: (■) 1.5%, (▲) 2.0%, (●) 2.5%.

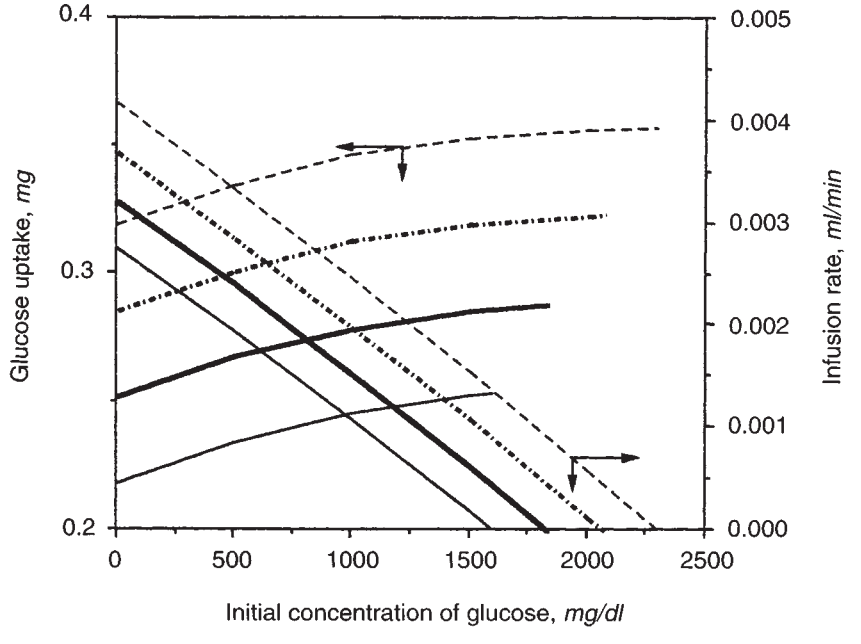

Fig. 8. *Differences of glucose uptake between bolus injection and continuous infusion at varying glucose concentrations as a function of dwell time.* Symbols represent the amount of water removed: (—) 1.0 ml; (—) 2.0 ml; (· –· –) 3.0 ml; (– – –) 4.0 ml.

lymphatic ducts in the peritoneal membrane as well as capillaries, and particularly several lymph lacunae on the diaphragm. Many investigators reported that these lacunae permit reabsorption of fluid, particles, cells and colloids into the body [19, 21, 22]. Furthermore, Breborowicz, Rodela and Oreopoulos indicated that lymphatic absorption rate was not steady during peritoneal dialysis and depended upon intraperitoneal pressure from the results of *in vivo* assessments [6].

In the newly proposed mass transport model we added the term of lymphatic transport to conventionally used diffusive and convective transport terms, assuming that the lymphatic flow rate was proportional to intraperitoneal pressure. Based upon this assumption, 1.0×10^{-4} to 1.5×10^{-4} kg/min/100 g body wt of lymphatic absorption coefficient of Wistar rats was numerically determined using equations (1) through (3).

Table 2 shows a comparison of KA and Lc between the

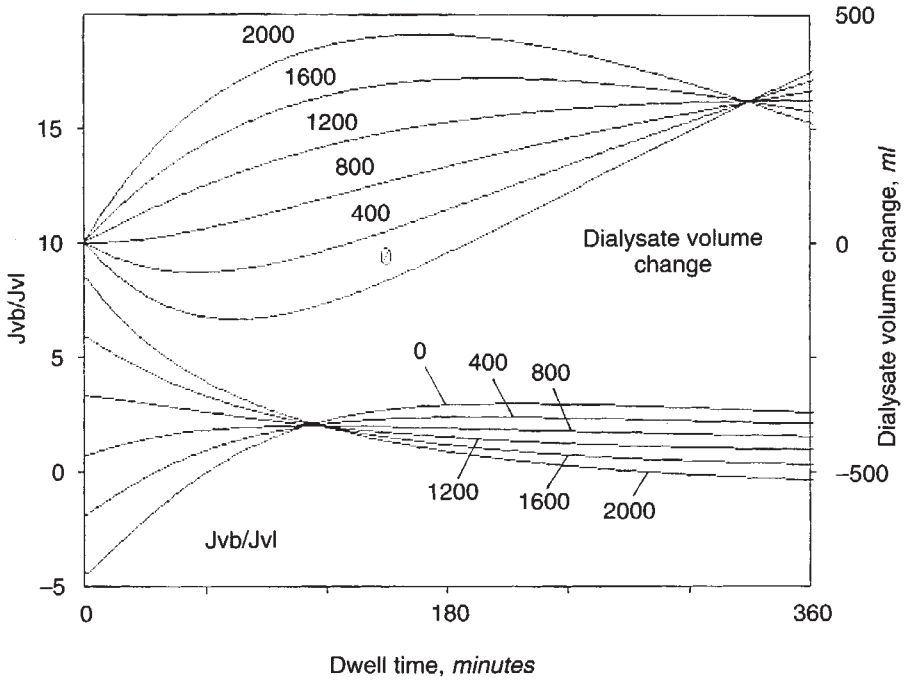

Fig. 9. *Changes in the ratio of lymphatic transport to convective transport, intraperitoneal dialysate volume and infusion rate at varying initial glucose concentrations.*

Table 2. Comparison of mass transport coefficient (ml/min) and hydraulic conducitivity (human: 60 kg)

	KA-glucose	KA-urea
Krediet [13]	10.7	24.8
Rippe [23]	16.5	29.1
Hallett [8]	—	17.1–18.6
Nakanishi [24]	6.1–18.5	—
Waniewski [17]	9.8–12.7	24.0–28.4
Popovich [25]	18.1	33.5
Yamashita [26]	8.35	23.3
This paper	5.5–24.4	6.7–27.1

Hydraulic conductivity *ml/min/mm Hg*

	Lp
Smeby [3]	0.033–0.17
Rippe [23]	0.08
Hallet [8]	0.014
This paper	0.007–0.047

values cited from previous literature and those of Wistar rats normalized by 60 kg of body weight using scaling factors of 1 to 0.7. When the scaling factor was closer to unity, the value of KA of urea N agreed reasonably, however, the KA value of glucose was about twice large than that of literature cited. Concerning values of Lc in the literature, there are no consistent values because these values were numerically estimated by the individual model. The value of Lc in this study was slightly larger than half of Rippe and Stelin's estimated value [23] and slightly larger than that by Smeby, Wideroë and Jörstad [3]. A good agreement between calculated and measured glucose concentrations indicates that transcellular passway of water flux proposed by Rippe and Stelin may be negligible. Although they estimated 35 to 50% of transcellular water transport to the total value, this number just corresponded to difference between our measured value and their estimated value. The value calculated by Smeby et al may be underestimated due to residual volume. Although our data appear reasonably but are underestimated with scaling factor of about 0.7, further investigation will be necessary to determine whether these disagreements are dominated by differences in species or the measurement method itself.

Differences in glucose uptake between the common CAPD and CAPD with glucose infusion in the clinical case of one man are computed using our model and illustrated in Figure 9, although further understanding of differences of mass transport characteristics and scaling factor among species is necessary. This result interestingly indicates that CAPD with glucose infusion at varying infusion rate alternates the ratio of lymphatic transport to convective transport while 10 to 20% less amount of glucose uptake could be achievable.

CAPD with glucose infusion may not only reduce the amount of glucose uptake, but may possibly prevent the deterioration of peritoneal membrane properties. Moreover, it lightens the feelings of abdomen pressure accompanied by a sudden increase of dialysate just after the injection of hypertonic dialysate because water removal occurs constantly in this method. Thus, CAPD with glucose infusion is very significant for the solution of problems of common CAPD. Finally, to install this method clinically, a method of infusion should be developed to consider the prevention of peritonitis and the freedom of the patient that will be also useful for chronic intraperitoneal drug administration.

Conclusion

A new CAPD mass transport model is proposed which takes into account lymphatic absorption. We assumed that lymphatic absorption was proportional to the volume of intraperitoneal dialysate.

Mass transport coefficient (KA) and hydraulic conductivity (Lc) were obtained by *in vivo* experiments using rats. KA of urea N and glucose were 0.045 to 0.066 and 0.041 to 0.063 (ml/min/100 g body wt), respectively, and Lp was 7.9×10^{-5} to 1.5×10^{-4} ml/min/mm Hg/100 g body wt.

To reduce glucose uptake a method of continuous infusion of glucose solution into dialysate was designed. From the results of computer simulation it is suggested that CAPD with glucose infusion alternates the ratio of lymphatic transport to convective transport and reduces glucose uptake up to 16% compared with common CAPD in which glucose concentration of dialysate ranged between 1.5% to 4% in six hours of dwell time.

Reprint requests to Takashi Horiuchi, D.Eng, Division of Applied Life Science, Graduate School of University of East Asia, 2-1 Ichinomiya Gakuencho, Shimonoseki-shi, Yamaguchi, Japan 751.

Appendix. Nomenclature

V_d: intraperitoneal dialysate volume, ml
C_b: concentration of solute in body fluid, mg/dl
C_d: concentration of solute in dialysate, mg/dl
$\bar{C}$: concentration of solute in membrane, mg/dl
KA: mass transport area coefficient, ml/min
J_{vb}: ultrafiltration rate, ml/min
J_{vl}: lymphatic absorption rate, ml/min
Lc: hydraulic conductivity, ml/min/mm Hg
lx: lymphatic absorption coefficient, kg/min
σ: Staverman reflection coefficient, –
OP: oncotic pressure, mm Hg
p: hydrostatic pressure, mm Hg
R: universal gas constant, l · atm/K/mol
T: absolute temperature, K

Acknowledgments

The authors are grateful to both Dr. Sumida (Sumida Medical Clinic, Japan) and Dr. Werynski (Polish Academy of Science, Poland) for valuable discussion.

References

1. Heaton A, Johnston DG, Burrin JM, Orskov V, Alberti KG, Kerr DN: Carbohydrate and lipid metabolism during continuous ambulatory peritoneal dialysis (CAPD): The effect of a single dialysis cycle. *Clin Sci* 65:539–545, 1983
2. Lindholm B, Bergström J: Nutritional aspects of CAPD, in *Continuous Ambulatory Peritoneal Dialysis*, edited by Gokal R, London, Pitman Publishing, 1986, p. 228–263
3. Smeby LC, Wideröe TE, Jörstad S: Individual differences in water transport during continuous peritoneal dialysis. (abstract) *Am Soc Artif Intern Organs J* 4:1727, 1981
4. Pyle WK, Moncrief JW, Popovich RP: Peritoneal transport evaluation in CAPD, in *CAPD Update*, New York, Masson Publishing USA, Inc, 1981, pp. 35–52
5. Wideröe TE, Smeby LC, Dahl K, Jörstad S: Definitions of differences and changes in peritoneal membrane water transport properties. *Artif Organs* 12:210–218, 1988
6. Breborowicz A, Rodela H, Oreopoulos DG: Effect of various factor on peritoneal lymphatic flow in rabbits. *Perit Dial Int* 9:85–90, 1989
7. Mactier RA, Khanna R, Twardowski ZJ, Moore H, No lph KD: Contribution of lymphatic absorption to loss of ultrafiltration and solute clearances in continuous ambulatory peritoneal dialysis. *J Clin Invest* 80:1311–1316, 1987
8. Hallet MD, Lysaght MJ, Farrell PC: The role of lymphatic drainage in peritoneal mass transfer. *Artif Organs* 13:28–34, 1989
9. Mactier RA, Khanna R: Absorption of fluid and solute from the peritoneal cavity—theoretic and therapeutic implications and applications. *Trans Am Soc Artif Intern Organs* 35:122–131, 1989
10. Mactier RA, Khanna R, Moore H, Russ L, Nolph KD, Groshong T: Kinetics of peritoneal dialysis in children—Role of lymphatics. *Kidney Int* 34:82–88, 1988
11. Mactier RA, Khanna R, Moore H, Twardowski ZJ, Nolph KD: Pharmacological reduction of lymphatic absorption from the peritoneal cavity—Increase net ultrafiltration and solute clearances in peritoneal dialysis. *Nephron* 50:229–232, 1988
12. Nolph KD, Mactier RA, Khanna R, Twardowski ZJ, Moore H, McGary T: The kinetics of ultrafiltration during peritoneal dialysis—The role of lymphatics. *Kidney Int* 32:219–226, 1987
13. Krediet RT, Struijk DG, Kooman GCM, Arisz L: Peritoneal fluid kinetics during CAPD measured with intraperitoneal dextran 70. *Trans Am Soc Artif Intern Organs* 37:662–667, 1991
14. Yoffey JM, Courtice FC: *Lymphatics, Lymph and the Lymphomyeloid Complex*. London, Academic Press, 1979, p. 295
15. Lindholm B, Werynski A, Bergström J: Kinetics of peritoneal dialysis with glycerol and glucose as osmotic agents. *Trans Am Soc Artif Intern Organs* 33:19–27, 1987
16. Lindholm B, Werynski A, Bergström J: Peritoneal dialysis with amino acid solutions: Fluid and solute transport kinetics. *Artif Organs* 12:2–10, 1988
17. Waniewski J, Werynski A, Heimburger O, Lindholm B: A comparative analysis of mass transport models in peritoneal dialysis. *Trans Am Soc Artif Intern Organs* 37(2):65–75, 1991
18. Rippe B, Perry MA, Granger DN: Permselectivity of the peritoneal membrane. *Microvasc Res* 29:89–102, 1985
19. Zink J, Greenway CV: Control of ascites absorption in anesthetized cats—Effects of intraperitoneal pressure, protein and furosemide diuresis. *Gastroenterology* 73:1119–1124, 1977
20. Dedrick RL: Interspecies scaling of regional drug delivery. *J Pharmaceutical Sci* 75(11):1047–1052, 1986
21. Flessner MF, Parker R, Sieber SM: Pertoneal lymphatic uptake of fibrinogen and erythrocytes in the rat. *Am J Physiol* 244:H89–H96, 1983
22. Abernethy NJ, Chin W, Hay JB, Rodela H, Oreopoulos D, Johnston MG: Lymphatic drainage of the peritoneal cavity in sheep. *Am J Physiol* 260:F353–F358, 1991
23. Rippe B, Stelin G: Simulations of peritoneal solute transport during CAPD—Application of two-pore formalism. *Kidney Int* 35:1234–1244, 1989
24. Nakanishi T, Tanaka Y, Fujii M, Fukuhara Y, Orita Y: Nonequilibrium thermodynamics of glucose transport in continuous ambulatory peritoneal dialysis, in *Machine Free Dialysis for Patient Convenience*, edited by Maekawa M, Kishimoto T, Nolph KD, Moncrief JW, Cleveland, ISAO Press, 1984, pp. 39–43
25. Popovich RP, Moncrief JW, Pyle WK: Transport kinetics, 6, in *Peritoneal Dialysis* (3rd ed), edited by Nolph KD, Kluwer Academic Publishers, Dordrecht, 1989, pp. 96–116
26. Yamashita A, Nagumo H, Hidai H, Kumano K, Iidaka K, Sakai T: Efficacy of diffusive and convective transport for solute removal in CAPD. *Jpn J Artif Organs* 14:111–114, 1985