"An Analysis of Mass Transport in Hemodialyzer Reuse"

by

Conrad P. Seghers

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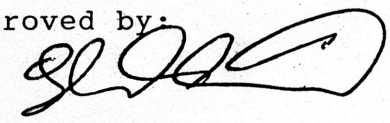

Dr. Gerald E. Miller

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ABSTRACT

The kidney is one of the most vital organs in the body. When a significant number of the kidney's functional units, the nephrons, are failing, an artificial means of fulfilling the kidney's duties is required in order to sustain life. The functions for which the kidney is responsible include the regulation of ion concentrations, waste product reabsorption, water volume control, and regulating the acid-base balance of the body.

One such means of artificial kidney functioning, hemodialysis, consists of the blood passing extracorporeally through a dialyzer. A dialyzer is essentially a semipermeable membrane across which products diffuse between the blood, which is on one side of the membrane, and the dialysate, which is on the other. Dialysate is normally a physiologic cleansing solution containing glucose, amino acids, vitamins, and other vital substances.

Dialyzers are meant to be single-use; however, it is common practice by many dialysis centers to reuse them often up to 30-40 times. The purpose of this research project is to attempt to prove that dialyzer reuse has a direct effect on the efficiency and thereby the mass transport of products across the semipermeable membrane.

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INTRODUCTION

The human kidneys are the most complex and fascinating mass transport devices in the body. They perform many vital functions required for human subsistance, all of which deal with blood filtration. These include excreting the end-products of protein metabolism such as urea, creatinine, and uric acid, as well as other wastes (sulfates and phenols) in the form of urine. The kidneys also regulate the concentrations of and remove excess amounts of sodium, chlorine, potassium, phosphates, and other ions. They control the body fluid volume by the excretion of water. In addition, by adjusting the levels of hydrogen and bicarbonate ions, the kidneys control the acid-base balance of the body.

The kidney is comprised of millions of individual functional units known as nephrons, each of which contains a capillary network, the glomerulus, and a system of tubules and collecting ducts. Both of these are then totally surrounded by a larger capillary bed. Approximately 1200ml/min, or twenty percent of the total blood flow, goes to the two kidneys. Of this amount 125 ml/min passes through the glomerular capillary network and enters the tubules of the nephron. This filtrate as it is now known is essentially blood plasma without proteins. Nevertheless, thirty grams of protein per day does go across the glomerulus and is excreted in the

urine. As the filtrate passes through the nephron solutes such as glucose and amino acids which the body wants to retain are reabsorbed, while wastes are excreted. Ions such as sodium and chlorine are reabsorbed only to the degree desired by the body. Normally 99.4% of the water passing through the nephron is reabsorbed by osmosis, resulting in an average of one liter per day of urine from 180 l/day of filtrate.

Kidneys have little regenerative capacity, and it is usually decided to install some type of artificial kidney if 90% of the natural kidneys' excretory capacity is non-functional. Renal failure refers to the inability of the kidneys to cope with large amounts of electrolytes and waste products. One-third of the normal number of nephrons can eliminate enough of the body's wastes so as not to cause serious waste accumulation in any body fluid. However, when the number of functional nephrons decreases further below this level urinary retention and ultimately death occur.

There are many methods to artificially remove the body of its waste products. Extracorporeally the two main techniques are ultrafiltration and fixed bed adsorption columns. Also, there are five main methods of dialysis, which involves the removal of wastes through diffusion across a membrane. These include peritoneal dialysis, wherein the abdominal cavity is filled with a cleansing fluid known as dialysate across the peritoneal membrane, gastrodialysis in which a cellophane bag is placed in the stomach and diffusion occurs, pleural dialy-

sis where the process is performed in the pleural (respiratory) cavity, and intestinal dialysis. The most common method of dialysis and the one to which the remainder of this paper will refer is haemodialysis, where the blood exchanges wastes and water with a dialysate solution outside of the body across a semipermeable membrane. A dialyzer, which is basically a semipermeable membrane inside a supporting structure, allows blood to flow on one side of the membrane, with the physiologic solution containing glucose, amino acids, major ions and other vital substances on the other. The dialysate is similar in composition to the normal body fluids with the exception of containing no waste products. Everything except blood cells and proteins transfers across the membrane.

All substances in dialysis including water, vitamins, carbohydrates, lipids and polypeptides are excreted, which is not the case in the nephron. It is generally not a problem to add glucose to the dialysate, but amino acids, vitamins and other essential substances can be very expensive. A supplemental diet containing vitamins, proteins and excess calories is thus required. This and decreased intestinal vital substance absorption lead to a poor general health in dialysis patients.

The dialyzer is then part of a larger hemodialysis machine, collectively referred to as an "artificial kidney." The remaining option for end-stage renal disease is a successful kidney transplant, but the lack of donors, risk of infection, and rejection by the body cause the other alternatives to be much preferred.

Waste products need not be removed daily, i.e., three days worth of wastes can be removed every third day. To totally cleanse the blood of a waste product one must maintain having none in the dialysate, while to adjust an item's concentration the dialysate must maintain the ultimate value of the product. Dialysis is a function of concentration gradients and is size discriminatory, larger molecular weight solutes clearing at much slower rates. These larger potentially toxic molecules can be monitored by vitamin B_{12} and inulin, innocuous middle weight substances. Inexpensive, high-flux membranes could clear these large substances; however, they often result in an increased fluid loss. Water must also be removed as it is both taken orally and created through the oxidation of foodstuffs. This can be achieved by either applying a net hydrostatic pressure gradient between the blood and dialysate or by making the dialysate hyperosmotic through the addition of extra glucose.

Hemodialyzers today are reliable, can be manufactured in large quantities, have few leaks or ruptures, and have no observable toxic effects. There are many ways to perform dialysis, using either a blood flow pump or the arteriovenous pressure gradient to move the fluids through the dialyzer. The directions of the blood versus the dialysate flow can be the same (co-current), opposite (counter-current), or perpendicular (cross-current). There are three basic models of dialyzers: the coil, the flat-plate, and the hollow fiber. This project was performed using the hollow fiber dialyzers countercurrently with

blood pumps. Figure 1 shows a standard hollow fiber dialyzer of the type used in the experiments. Figure two shows this dialyzer in an entire artificial kidney setup, as is found in virtually all nephrology clinics.

An ideal dialyzer removes nitrogenous and toxic wastes, excess ions, and water, has a small priming volume, a small resistance so as not to require a blood pump which can cause hemolysis, is presterilized and is blood compatible. Almost all dialyzers are manufactured with the intention of being single-use. Nevertheless, over 75% of hemodialysis patients today undergo treatment with single-use dialyzers that have been used often up to forty times.[1] The reasons for this practice are mainly economical. In addition, the first-use dialyzer syndrome must be avoided, wherin toxic eluates of the manufacturing process cause adverse reactions in the patient. Another advantage to reuse is the lack of legal supervision at present on the issue, as opposed to the many regulations on the manufacturing of hemodialyzers.

Many studies have been performed on the economic and legal aspects of the controversial issue of dialyzer reuse. The majority of conclusions being reached are that reusing hemodialyzers has little or no effect on the quality of the dialysis treatment. The purpose of this research project is to attempt to disprove these seemingly impossible statements, by showing that the reuse of hemodialyzers causes marked effects on mass transport and the rate of ultrafiltration by decreasing

the cross-sectional membrane area.

The main components of a dialyzer are the blood compartment, the dialysate compartment, and the semipermeable membrane. In hollow fiber dialyzers, blood passes on the inside of thousands of hollow fibers, with the dialysate on the outside. Parameters to measure dialyzer performance include clearance, dialysance, ultrafiltration rates, compliance, and priming volumes. By making hemodialyzers of the single-use variety, infections are reduced, medical and diagnostic qualities improved, unit costs reduced, and efficiency, reliability and dependability are improved. Dialyzers of this form can be mass produced and made non-toxic, non-pyrogenic, and sterile.

Reusing hemodialyzers was first introduced by Shaldon in Europe in 1964. To reprocess these dialyzers, an initial rinsing with water is performed. The dialysate outflow is periodically clamped during this rinse, creating pressure which cleans out much of the blood residue. This is followed by a cleaning with hydrogen peroxide or sodium hypochlorite, and then a rinse with formaldehyde to resterilize the unit. It is recommended before each treatment to rerinse the dialyzer with a 0.9% physiologic saline solution to assure that all of the formaldehyde is gone and thereby prevent adverse patient reactions. This reprocessing of hemodialyzers can be done mechanically, being more efficient and reducing staff hepatitis.

Disadvantages to dialyzer reuse are decreased dialyzer

efficiency, patient reactions to the formaldehyde, residual blood clinging to the membrane, thrombi formation, increased pyrogenic reactions due to the bacterial endotoxins, adverse patient reactions such as fever and infections (hepatitis, shunt infections, and septicemia), and decreased transport of large molecular weight molecules through the membrane. Over time, blood and protein components are deposited on the membrane, causing decreased surface area, less large molecular diffusion and increased time required for dialysis due to the smaller area. Besides the obvious economic and discomfort disadvantages to increased time per treatment, the small molecule deficiency syndrome caused by increased small molecule removal can occur. These changes in the membrane permeability and structure lead to decreased uraemic toxin removal as well. With continual reuse of the membrane, increased blood leaks out of the dialyzer and there is a loss of dialyzer blood volume due to the clotting, causing the decreased middle molecule clearance.

Formaldehyde poisoning can induce burning numb feelings, hemolysis, altered pH, and red blood cell metabolic defects. It can also alter the N-antigen in the blood residues left in the dialyzer, which upon reuse are flushed back into the body. Anti-N antibodies that agglutinate when combined with N-antigen are formed, causing an increased risk of anemia and a potential for problems should a kidney transplant ever be desired. A rapid but reversible neutropenia and leukopenia often result,

as well as arterial hypoxemia from perfusion defects.

With every usage there is a loss in effective membrane area from thrombi (fibrin deposition and platelet aggregation), and the accumulation of other debris. To attempt to prevent thrombi the anticoagulant heparin is administered throughout the treatment session. "To prevent bleeding in the patient as a result of the heparin an anti-heparin substance, protamine, is infused into the blood as it is returned to the patient."[2] The thrombi and debris cause changes in the overall mass transfer resistance. The decreased membrane area leads to a decreased priming volume with reuse, causing a higher blood flow rate in open unclogged fibers as the total volume flow rate remains constant. By measuring the priming volume one can thus predict the change in clearance of solutes and the ultrafiltration capacity.[3]

Functional performance is a measure of the clearance of small molecules, ultrafiltration, and blood loss. Enhanced biocompatibility, or leukopenia, which is a decrease in the number of white blood cells, is also a factor. Hoenich claims that the reuse of dialyzers has no effect on functional performance except for blood loss. This opinion is shared by Gagnon, who states that the membrane permeability to small solutes such as urea and creatinine, as well as larger ones such as Vitamin B_{12}, is unaffected. Gagnon claims that a standard dialysate solution is comprised of sodium, potassium, calcium, magesium, chlorine and acetate. Figure 3 shows the main components of the glomerular filtrate and urine, the concentrations of which in the artificial process the dialysate

is trying to regulate. When artificial in vitro blood is used saline containing urea, creatinine, phosphate and Vitamin B_{12} is substituted. Average blood flow rates during dialysis are 100-200 ml/min, while dialysate is 500 ml/min. Gagnon also suggests the reprocessing of dialyzers before their first use so as to detect membrane disruption by increased ultrafiltration rates. This will therefore prevent blood leaks. Another advantage to initial reprocessing is to obtain individual dialyzer measurements rather than bulk ones for such characteristics as priming volume, as well as removing toxic eluates causing the first-use dialyzer syndrome. Hemodialysis neutropenia (a decrease in the number of neutrophils), and arterial hypoxemia (oxygen deficiency in the blood) were Gagnon's only two observed ill-efects of reuse.

Bourke claims that up to a seventy percent cost reduction can be achieved through dialyzer reuse with no compromise on performance. His projected economic savings may not yet be in the proper perspective; however, as the costs for labor, storage and processing reused dialyzers as well as the increased medical complications that may accompany the procedure may actually in the long term far surpass the projected $6,000 annual savings per patient. The two main risks of reuse are formaldehyde poisoning and anti-N antibodies. All of the afore-mentioned articles are pro-reuse both for the economic and first-use syndrome factors. They set self-imposed guidelines, the most common being "It would appear prudent to restrict reuse to devices in which priming volume loss is less than twenty percent."[4]

There are just as many articles portraying the negative effects of reuse however, from decreased efficiency, increased treatment time required, and the ill side-effects.[5] HIMA-Reuse of Single-Use Hemodialyzers makes the statement that until a patient's rights to informed consent are protected and the safety and efficacy of dialyzer reuse is established "...the uncontrolled reuse of dialyzers as practiced by some dialysis centers should be discontinued."[6] The National Kidney Foundation perhaps comes to the best conclusion of all, in that dialysis is a no-win situation in which "New dialyzers contain potentially toxic residues of the manufacturing process,... while used dialyzers contain potentially toxic residues of the reprocessing procedure."[7] Most artificial kidneys can clear 100-200 ml of plasma per minute of urea, twice as much as the two natural kidneys combined whose clearance is 70 ml per minute. However, due to danger from excess heparin, blood hemolysis, and infection, artificial kidneys can be used a maximum of twelve hours every three days.[2]

Once again, the objective of this project is to come to a conclusion on the ambiguous and much debated undecided issue of the reuse of hemodialyzers, and specifically whether mass transport from decreased membrane area and thereby the efficiency of the dialyzer is affected.

METHODS

This experiment was conducted using TAF 06, TAF 08, and

TAF 10 Model Dialyzers, whose effective surface areas are 0.6, 0.8, and 1.0 m^2 and priming volumes are 46, 56, and 65 ml respectively. Figure 4 gives further characteristics of these dialyzers. The devices contained cellulose acetate or Cuprophane membranes and had all been used multiple times. Their cleaning and testing before each previous reuse was performed with a Seratronics DRS-4 Dialyzer Cleaner. The dialyzers ranged in price from $13 to $16 each.

For the blood solution, physiologic 0.85%, or 290 milliosmoles per liter, saline was used in which 60 milliosmoles per liter, or 360 mg%, of urea had been added. The dialysate solution was pure physiologic saline. Both volumes of these "blood" and "dialysate" solutions were 1.5 liters. The urea level of 360 mg% is within the normal human physiologic limits and was randomly chosen to be added to the "blood" portion of the experiment. As there was 1.5 liters in the blood compartment: $\frac{360 \text{ mg}}{100 \text{ ml}} \times 15 = 5.4\text{g}$ of urea was added. This translates to:

$\frac{5.4 \text{ g}}{1.5}$ or 3.6 g/liter, which is equivalent to

$3.6 \text{ g/l} \times \frac{1 \text{ mole urea}}{60 \text{ g}} = 60$ milliosmoles/liter.

From both the blood and dialysate compartments the fluids travelled using flow pumps into rotometers, which regulated the rates, Q, of fluid flow. The "blood" solution was set on 100 ml/min, while the dialysate was running at 420 ml/minute. From the rotometers the fluids travelled counter-currently through the dialyzer and then back to the original 1.5 liter compart-

ments. A diagram of the exact experimental configuration used is seen in Figure 5. Samples of both fluid compartments were taken at regular intervals and their concentrations of urea measured and tabulated with a Precision Osmette Osmometer.

RESULTS

Raw experimental data can be found in Appendix A. Equilibrium times were extrapolated from this raw data. An important graph which can be constructed from this information is that of concentration versus time. Figure 6 shows a diagram of this graph for both a new ideal dialyzer and one that has been heavily reused and is thus no longer efficient. For the new dialyzer, it can be seen that the initial slope of the curve is very steep. This leads to a rapid equilibrium time of approximately ten minutes. The inverse of this, with a gradual slope and prolonged equilibrium time, is seen on the curve for the reused dialyzer. Concentration versus time graphs can be found in six sets in Appendix B.

Figure 7 shows a graph of the equilibrium times plotted against the number of reuses. The equilibrium time data is seen in Figure 8. A linear regression was performed on these numbers in which Line A of $y=31.5207 + 0.0793138x$ was obtained. However, when the three out of bounds points (13,24), (19,30) and (35,30) were excluded, equation B of $y=29.8713 + 0.32101x$ resulted.

CONCLUSION

When a linear regression is performed on the data relating equilibrium times to dialyzer reuse, an almost horizontal line is obtained. This seems to show virtually no correlation between reuse and equilibrium time. This would mean that mass transport and dialyzer efficiency is not affected by dialyzer reuse. However, when the three extraneous points (13,24), (19,30) and (35,30) are deleted from the data, a more realistic curve is obtained. This second line, $y=29.87 + 0.32x$, shows that a dialyzer that has been reused 25 times requires an additional eight minutes to achieve equilibrium. These experiments were conducted over a half-hour period, while the duration of a normal dialysis session is nine times that, or 4½ hours. Therefore, it can be extrapolated that dialyzer reuse might result in a 72 minute time difference from new ideal dialyzers.

If with every treatment 72 additional minutes are required for equilibration, the increased discomfort, cost to the patient and cost to the dialysis center due to the reuse of hemodialyzers is immense. However, many centers set a limit to the length of the treatment session. This means that a patient on a reused dialyzer in a fixed session length is receiving a far less beneficial dialysis session than had a new dialyzer been used.

In this experiment, the largest difficulties were in the area of experimental errors. The reading of concentrations from the Osmometer, the exact time of and duration of taking the

samples of blood and dialysate, and the fact that all of the equipment had to be extraordinarily clean may all be sources of error. One speck of dust in a test tube could raise the Osmometer's reading of the concentration of a sample by 30 milliosmoles. Another problem was that all dialyzers, whether new or reused, required 25-45 minutes to equilibrate. As all samples were taken in minutes, and not fractions thereof, this means that only 20 data points were available. In this area of 20 points dialyzers from 3 to 35 reuses, or 33 points had to be plotted, which could lead to some inaccuracy.

One as yet unexplained observation was that for the two solutions which began at 280 and 340 milliosmoles/liter, the final equilibrium point was not 310 milliosmoles/liter. The blood solution in most cases would decrease 35 milliosmoles, while the dialysate increased only 25 milliosmoles to reach equilibrium. The blood solution in the first three minutes of the experiments would also lose 10-20 milliosmoles of urea, while at the same time inexplicably the dialysate concentration would either remain constant or even decrease.

The conclusion reached here is that it is quite probable that reusing hemodialyzers is having a significant impact on the efficiency, mass transport and equilibration time of the dialysis process. However, further study is necessary to eliminate experimental errors and other uncertainties.

Future work might involve a study of the dangers and disadvantages as well as the advantages of reusing hemodialyzers.

The dangers include formaldehyde reactions, thrombi, fever and infection. Other areas requiring study are the effects of dialysis treatment, caused by the possible decreased membrane area and decreased dialyzer efficiency. Advantages at present to reuse are the possible cost benefits and lack of legal supervision as opposed to the numerous regulations on the manufacturing of hemodialyzers. Possible legal mandates and laws governing reusage need to be proposed after an in-depth study.

Methods of reuse could be evaluated, addressing the specific compounds used in the cleaning, resterilizing, and testing of dialyzers. New procedures could be devised, and the optimal method would then be chosen. Another area of hemodialyzer reuse to which little or no attention has yet been focused is the development of protocols. Standards for types and methods of cleaning, limits on a safe maximum number of reuses, and standards for the evaluation of a reused dialyzer's performance could be set.

Figure 1- Hollow Fiber Dialyzer

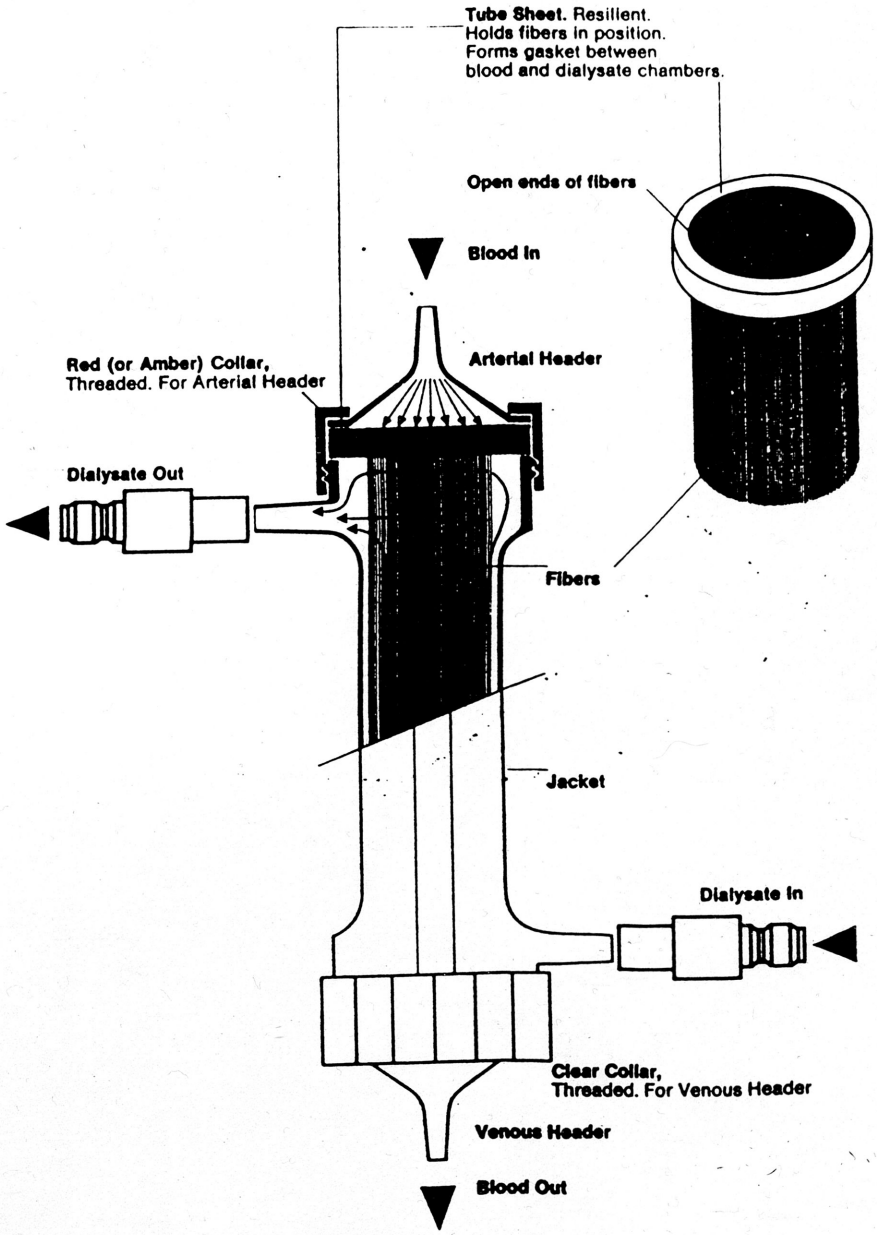


Figure 2
Functional Diagram of an Artificial Kidney

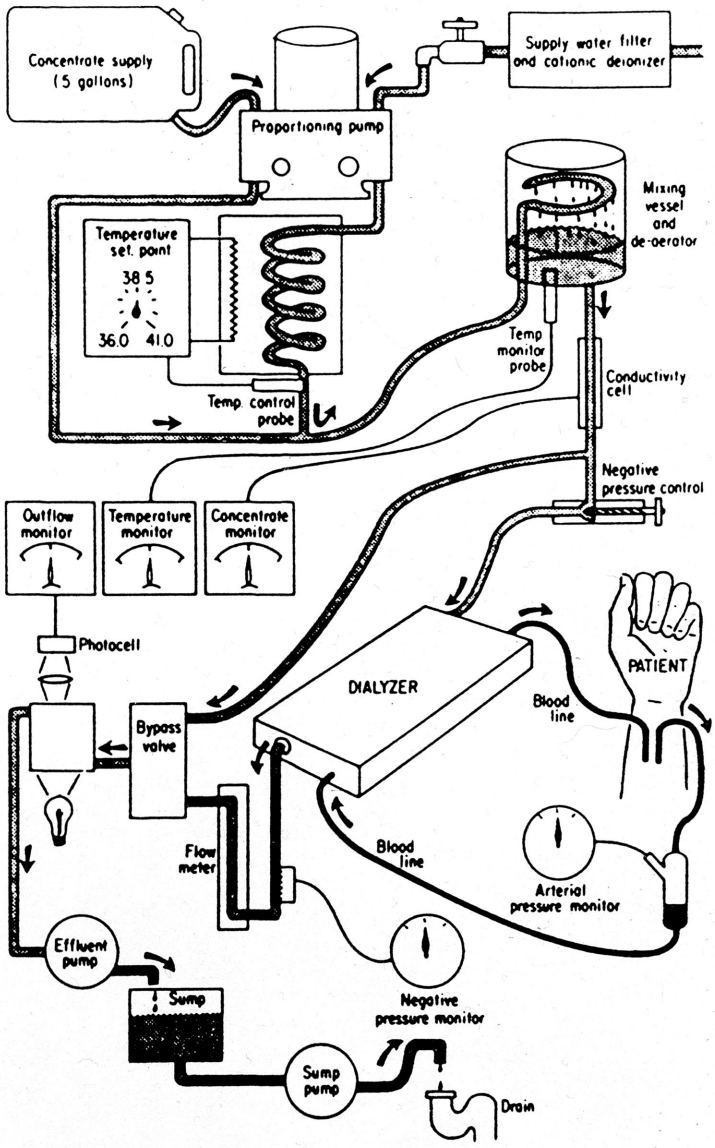


Figure 3

TABLE 8.1

Relative Concentrations of Substances in the Glomerular Filtrate and in the Urine[a]

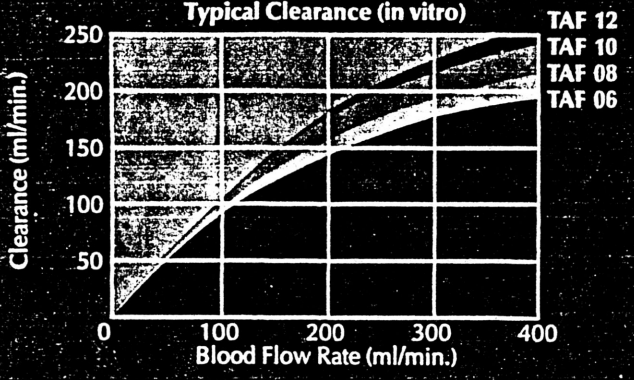
	Glomerular filtrate (125 ml/min)		Urine (1 ml/min)		Conc. urine/ conc. plasma (plasma clearance per minute)
	Quantity/min	Concentration	Quantity/min	Concentration	
Na^+	17.7 meq	142 meq/liter	0.128 meq	128 meq/liter	0.9
K^+	0.63	5	0.06	60	12
Ca^{2+}	0.5	4	0.0048	4.8	1.2
Mg^{2+}	0.38	3	0.015	15	5.0
Cl^-	12.9	103	0.134	134	1.3
HCO_3^-	3.5	28	0.014	14	0.5
$H_2PO_4^-$ / HPO_4^{2-}	0.25	2	0.05	50	25
SO_4^{2-}	0.09	0.7	0.033	33	47
Glucose	125 mg	100 mg%	0 mg	0 mg%	0.0
Urea	33	26	18.2	1820	70
Uric acid	3.8	3	0.42	42	14
Creatinine	1.4	1.1	1.96	196	140
Inulin	—	—	—	—	125
Diodrast	—	—	—	—	560
PAH	—	—	—	—	585

[a]From Guyton (1971), p. 404.

Performance Characteristics

Urea

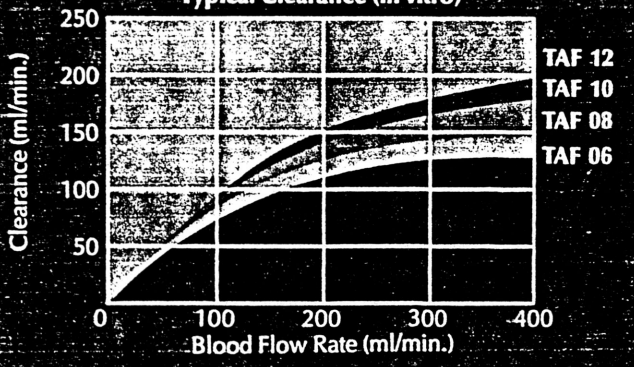
Typical Clearance (in vitro)



	QB (ml/min.)			
	QB 100ml	200	300	400
TAF 06	92	145	177	196
TAF 08	95	160	196	217
TAF 10	96	170	216	240
TAF 12	97	180	232	260

Creatinine

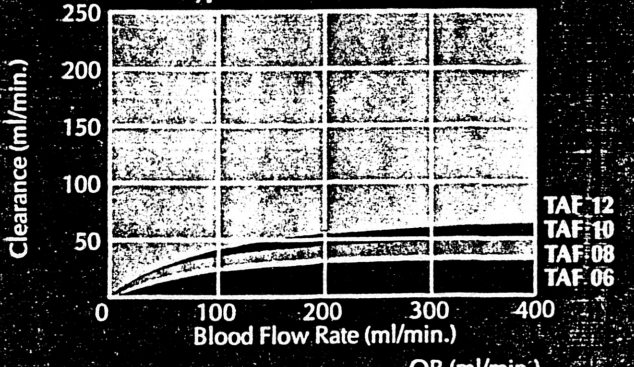
Typical Clearance (in vitro)



	QB (ml/min.)			
	QB 100ml	200	300	400
TAF 06	78	115	130	134
TAF 08	85	133	148	156
TAF 10	91	143	170	182
TAF 12	96	153	188	206

VB_{12}

Typical Clearance (in vitro)



	QB (ml/min.)			
	QB 100ml	200	300	400
TAF 06	26	32	32	33
TAF 08	33	39	40	41
TAF 10	39	45	48	48
TAF 12	45	53	57	58

The flow resistance of dialysate compartment is 30 mmHg on average at Qd: 500 ml/min.

Specifications

Effective Length:	178 mm
No. of Fibers:	5,700
Effective Surface:	0.6 m^2
Total Blood Volume:	46 ml
Expected UFR: (in vivo)	2.3

TAF 08

Effective Length:	178 mm
No. of Fibers:	7,100
Effective Surface:	0.8 m^2
Total Blood Volume:	56 ml
Expected UFR: (in vivo)	2.8

TAF 10

Effective Length:	235 mm
No. of Fibers:	6,800
Effective Surface:	1.0 m^2
Total Blood Volume:	65 ml
Expected UFR: (in vivo)	3.5

Effective Length:	235 mm
No. of Fibers:	8,300
Effective Surface:	1.2 m^2
Total Blood Volume:	80 ml
Expected UFR: (in vivo)	4.2

Figure 4. Characteristics and Specifications of the TAF Model Dialyzers

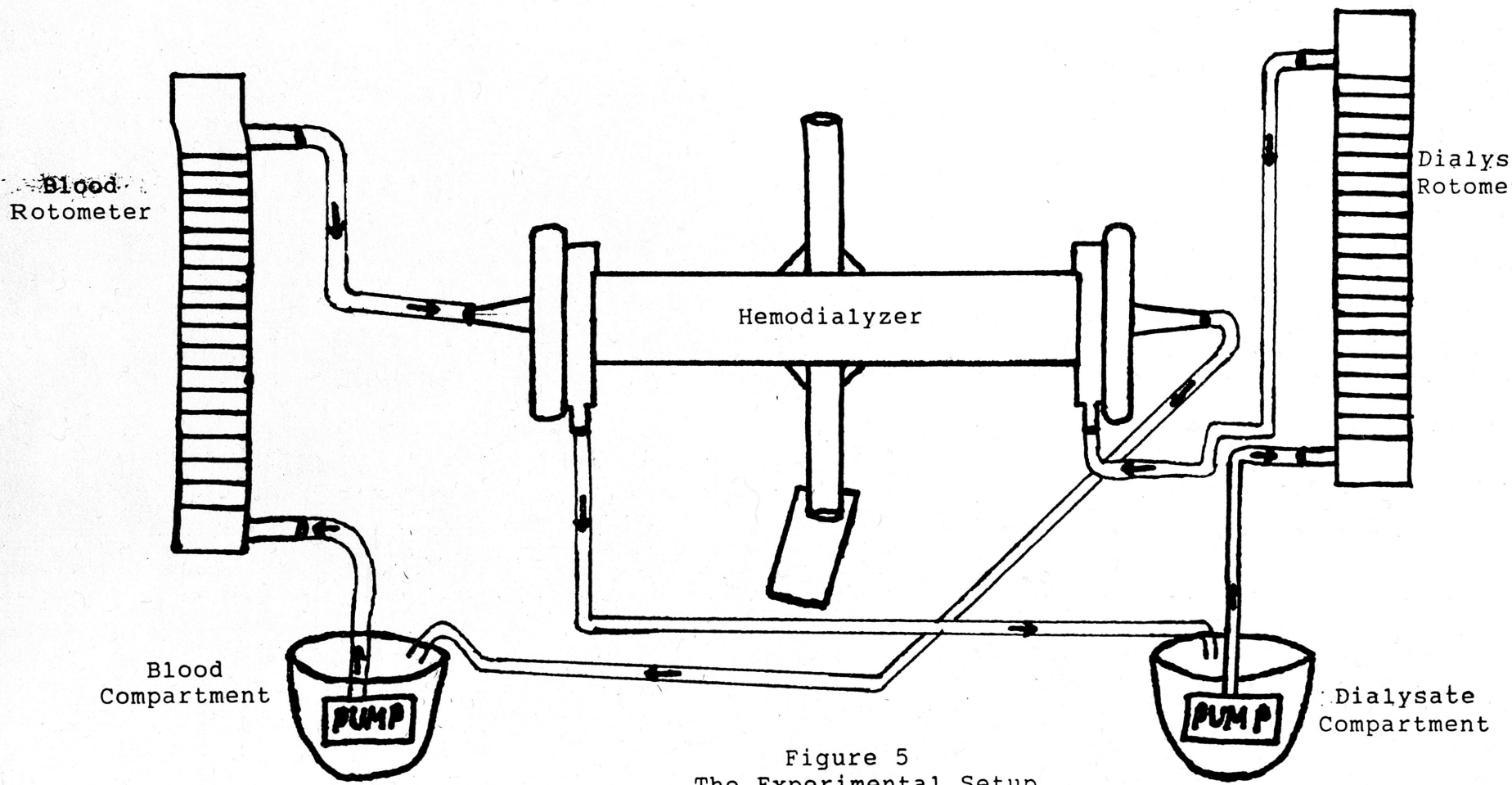


Figure 5
The Experimental Setup

Figure 6
Concentration Versus Time For A New And
Reused Dialyzer

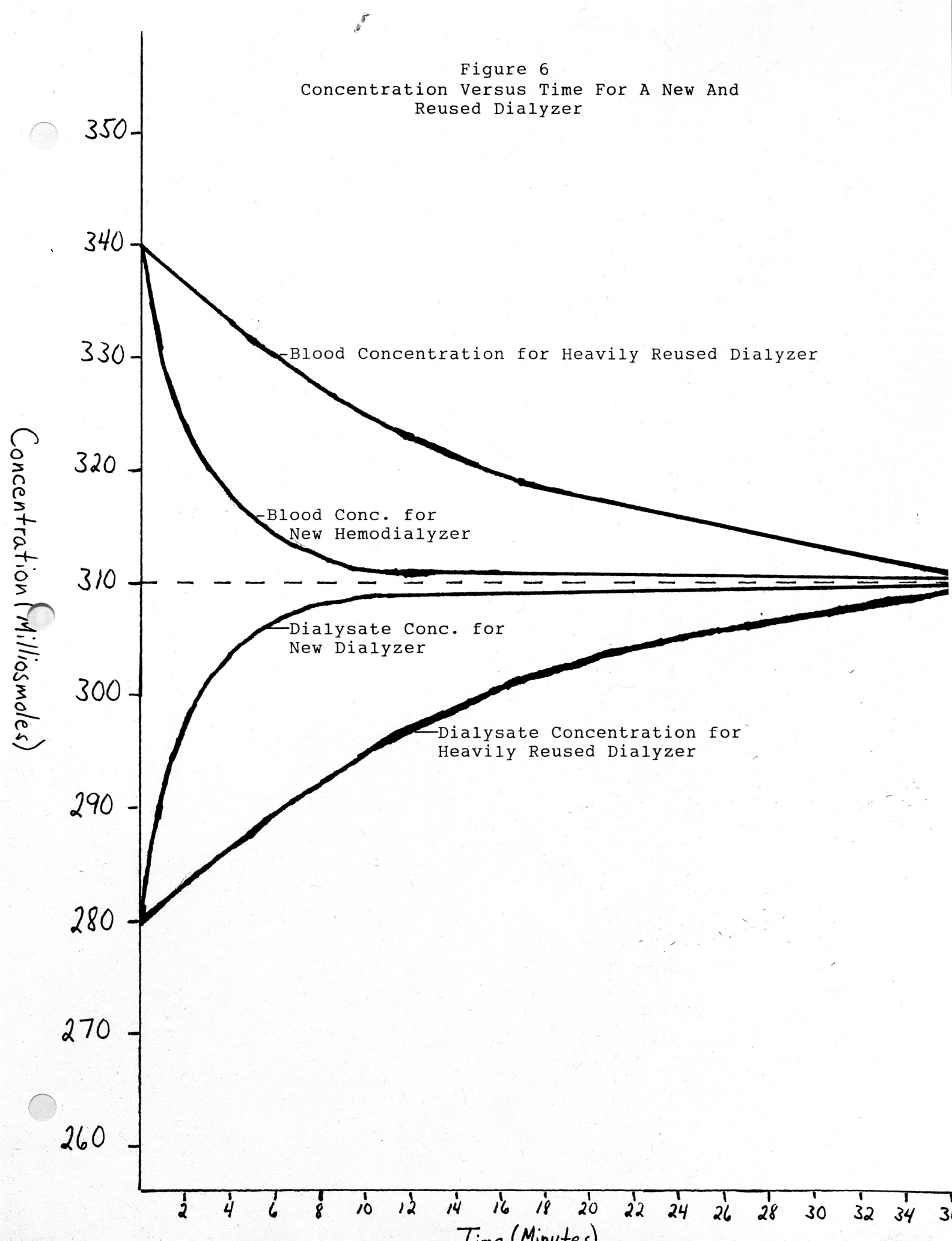


Figure 7-Equilibrium Time Versus Reuse

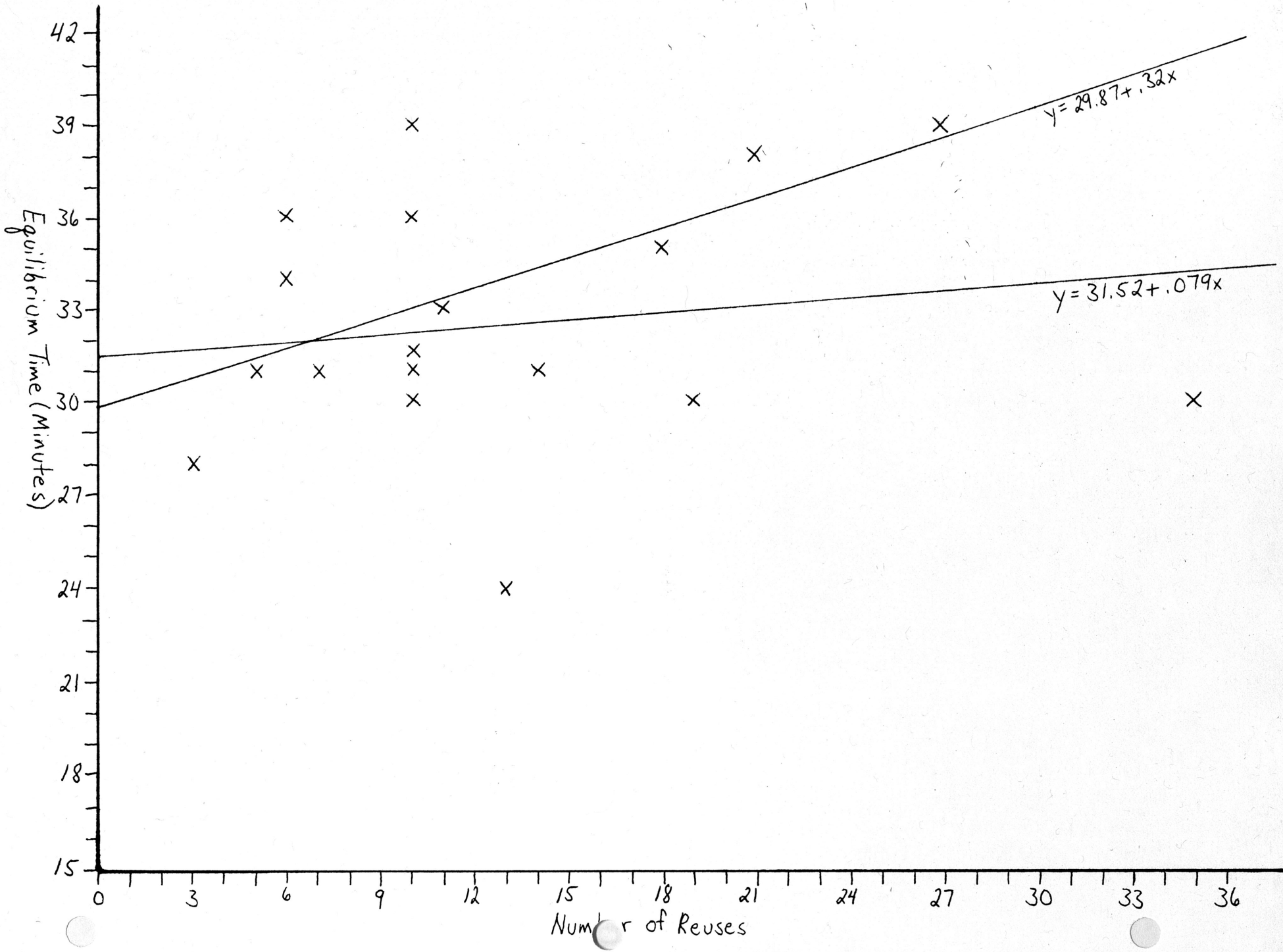


Figure 8

Experimental and Expected Values for Equilibrium Times

Number of Reuses	Actual Equil. Time Value (Minutes)	Expected Value A (Minutes)	Percent Difference for Line A	Expected Value B (Minutes)	Percent Difference for Line B
3	28	31.759	11.8	30.834	9.2
5	31	31.917	2.9	31.476	1.5
6	34	31.997	6.3	31.797	6.9
6	36	31.997	12.5	31.797	13.2
7	31	32.076	3.4	32.118	3.5
10	30	32.314	7.2	33.081	9.3
10	31	32.314	4.1	33.081	6.3
10	31	32.314	4.1	33.081	6.3
10	36	32.314	11.4	33.081	8.8
10	39	32.314	20.7	33.081	17.9
11	33	32.393	1.9	33.402	1.2
13	24	32.552	26.3	(34.044)	(29.5)
14	30	32.631	8.1	34.365	12.7
18	35	32.948	6.2	35.649	1.8
19	30	33.028	9.2	(35.971)	(16.6)
21	38	33.186	14.5	36.613	3.8
27	39	33.662	15.9	38.539	1.2
35	30	34.297	12.5	(41.107)	(27.0)
		Avg. % Difference	9.92		6.90

Expected Values A are for the line:

$y=31.5207 + 0.0793138x$ correlation coeff. 0.1626

Expected Values B are for the line in which points (13,24) (19,30) and (35,30) have been omitted:

$y=29.8713 + 0.321013x$ correlation coeff. 0.5854

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7 Revised Standards for Reuse of Hemodialyzers-National Kidney Foundation. American Journal of Kidney Diseases 6(1984) 466-468

Appendix A
(Raw Experimental Data)

Experiment 1- 3 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	336	278
1		
2		
3	321	276
4		
5		
6	317	278
7		
8		
9	305	285
10		
11		
12		
13		
14		
15		
16		
17		
18	300	293
19		
20		
21	300	
22		
23	298	294
24	298	294
25		
26	300	297
27		
28	296	296
29	300	297
30		
31	298	296
32		
33	299	298
34		
35	299	299
36	299	295
37	298	298
38		
39	295	296
40		
41		
42		

Experiment 2- 5 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	340	279
1		
2		
3	320	280
4		
5		
6	313	284
7		
8		
9	309	288
10		
11		
12		
13		
14		
15		
16		
17		
18	304	295
19		
20		
21		
22		
23		
24	301	297
25		
26	305	299
27		
28	300	298
29		
30	300	298
31		
32	300	299
33		
34	303	299
35		
36	311	305
37		
38	303	307
39		
40	326	337
41		
42		

Experiment 3- 6 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	344	281
1		
2		
3	320	281
4		
5		
6	318	315
7		
8		
9	315	
10		
11		
12	312	
13		
14		
15		
16	309	294
17		
18		
19		
20	312	297
21		
22		
23		
24		
25	308	300
26		
27		
28		
29		
30	305	300
31		
32		
33		
34		
35	313	302
36		
37		
38		
39		
40	303	303

Experiment 4- 6 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	337	277
1		
2		
3	318	276
4		
5		
6	314	282
7		
8		
9	309	287
10		
11		
12		
13		
14		
15		
16		
17		
18	304	295
19		
20		
21		
22		
23		
24	301	296
25		
26	301	295
27		
28	302	297
29		
30	301	299
31		
32	299	297
33		
34	299	297
35		
36	298	298
37		
38	320	320
39		
40		
41		
42	300	299

Experiment 5- 7 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	338	279
1		
2		
3	324	278
4		
5		
6	316	282
7		
8		
9	308	286
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20	301	296
21		
22		
23		
24	299	295
25		
26		
27		295
28	298	296
29		
30	299	296
31		
32	299	297
33	299	315
34	300	301
35	298	299
36	299	302
37		
38	298	308

Experiment 6- 10 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	342	278
1		
2		
3	330	278
4		
5		
6	318	282
7		
8		
9	312	284
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20	300	292
21		
22		
23		
24		
25		
26	299	
27		
28	299	294
29		
30	298	297
31		
32	297	296
33		
34	297	297
35		
36		
37	296	296
38	291	293
39	297	293
40	296	297
41		
42	296	296

Experiment 7- 10 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	341	282
1		
2		
3	322	282
4		
5		
6	318	287
7		
8		
9	312	289
10		
11		
12		
13	307	294
14		
15		
16		
17	305	294
18		
19		
20		
21	305	299
22		
23		
24		
25	306	303
26		
27		
28		
29		
30	302	302
31		
32		
33		
34		
35		

Experiment 8- 10 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	337	279
1		
2		
3	315	280
4		
5		
6	312	283
7		
8		
9	324	300
10		
11		
12		
13	317	297
14		
15		
16		
17	306	293
18		
19		
20		
21	303	295
22		
23		
24		
25	301	296
26		
27		
28		
29		
30	300	296
31		
32		
33		
34		
35		
36	300	298

Experiment 9- 10 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	339	278
1		
2		
3	321	276
4		
5		
6	316	285
7		
8		
9	309	287
10		
11		
12		
13		
14		
15		
16		
17		
18	302	293
19		
20		
21		
22		
23		
24	300	296
25		
26		
27	301	297
28		
29		
30	300	297
31	298	299
32		
33	298	296
34		
35	299	299
36		
37	322	320
38		
39		
40		

Experiment 10- 10 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	341	284
1		
2		
3	323	281
4		
5		
6	318	286
7		
8		
9		
10	311	288
11		
12		
13		
14		
15	309	292
16		
17		
18		
19		
20	308	294
21		
22		
23		
24		
25	304	297
26		
27		
28		
29		
30	304	298
31		
32		
33		
34		
35	303	300

Experiment 11- 11 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	332	274
1		
2		
3	320	261
4		
5		
6	317	285
7		
8		
9	320	290
10		
11		
12	307	293
13		
14		
15		
16	306	294
17		
18		
19		
20	303	296
21		
22		
23		
24		
25	305	298
26		
27		
28		
29		
30	302	300

Experiment 12- 13 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	341	283
1		
2		
3		
4	321	286
5		
6		
7		
8	315	293
9		
10		
11		
12	309	296
13		
14		
15		
16	308	297
17		
18		
19		
20	304	300
21		
22		
23		
24	305	304
25		
26		
27		
28		
29		
30	305	303
31		
32		
33		
34		
35		
36	304	303

Experiment 13- 14 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	360	278
1		
2		
3		
4		
5		
6	327	304
7		
8		
9		
10		
11		
12	308	319
13		
14		
15		
16		
17		
18	330	303
19		
20		
21		
22		
23		
24	308	304
25		
26		
27		
28		
29		
30	309	309

Experiment 14- 18 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	334	279
1		
2		
3	323	284
4		
5		
6	316	286
7		
8		
9	317	291
10		
11		
12	313	297
13		
14		
15		
16	309	296
17		
18		
19		
20	309	298
21		
22		
23		
24		
25	307	300
26		
27		
28		
29		
30	307	301

Experiment 15- 19 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	339	282
1		
2		
3		
4	326	286
5		
6		
7		
8	319	293
9		
10		
11		
12	310	295
13		
14		
15		
16	308	
17		
18		
19		
20	305	
21		
22		
23		
24		
25	306	303
26		
27		
28		
29		
30	303	303

Experiment 16- 21 Reuses

Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration Milliosmoles)
0	337	278
1		
2		
3	325	280
4		
5		
6	341	285
7		
8		
9		
10	326	294
11		
12		
13		
14		
15	310	296
16		
17		
18		
19		
20	308	298
21		
22		
23		
24		
25	307	301
26		
27		
28		
29		
30		
31		
32	306	303
33		
34		
35		
36		
37	305	303

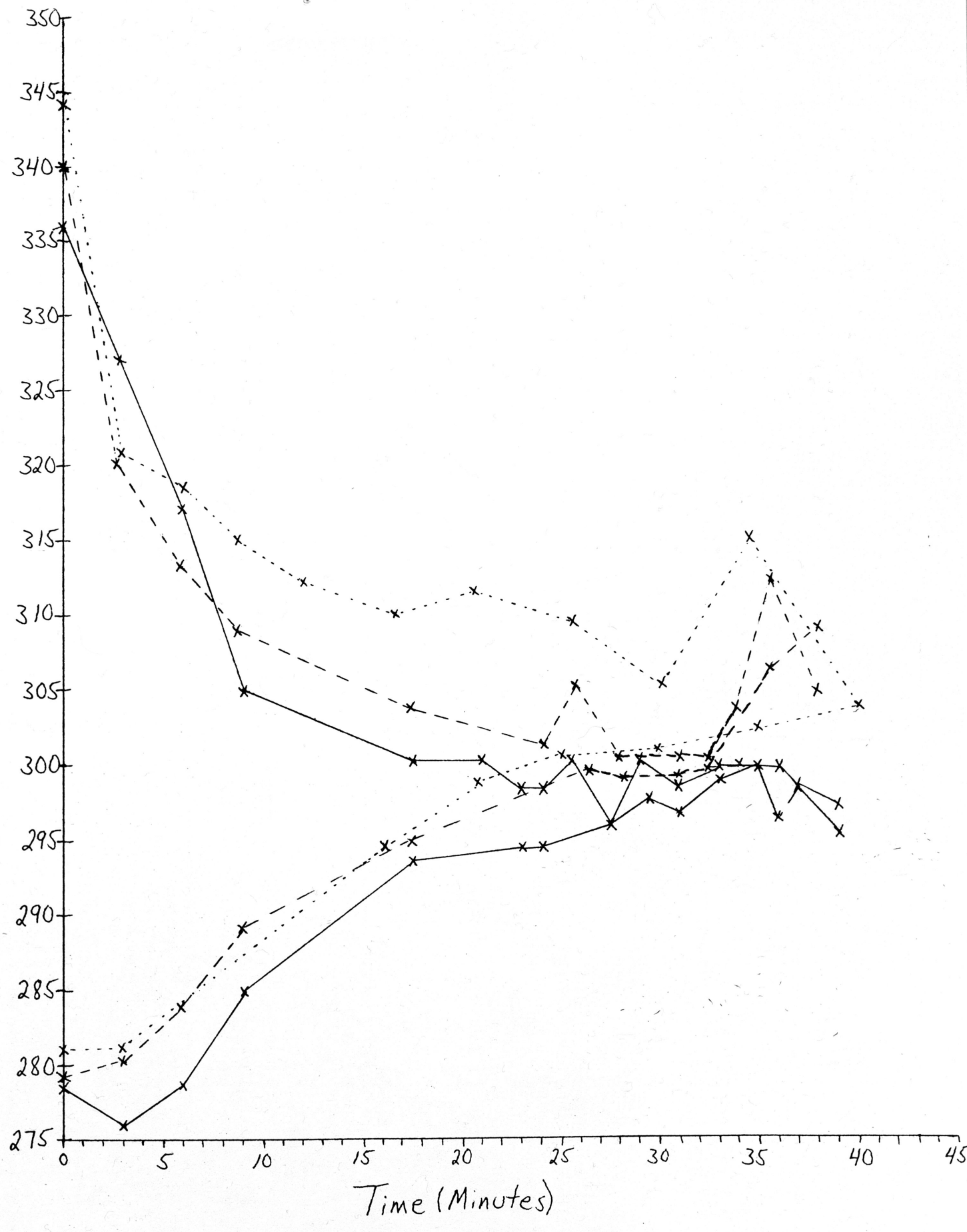
Experiment 17- 27 Reuses

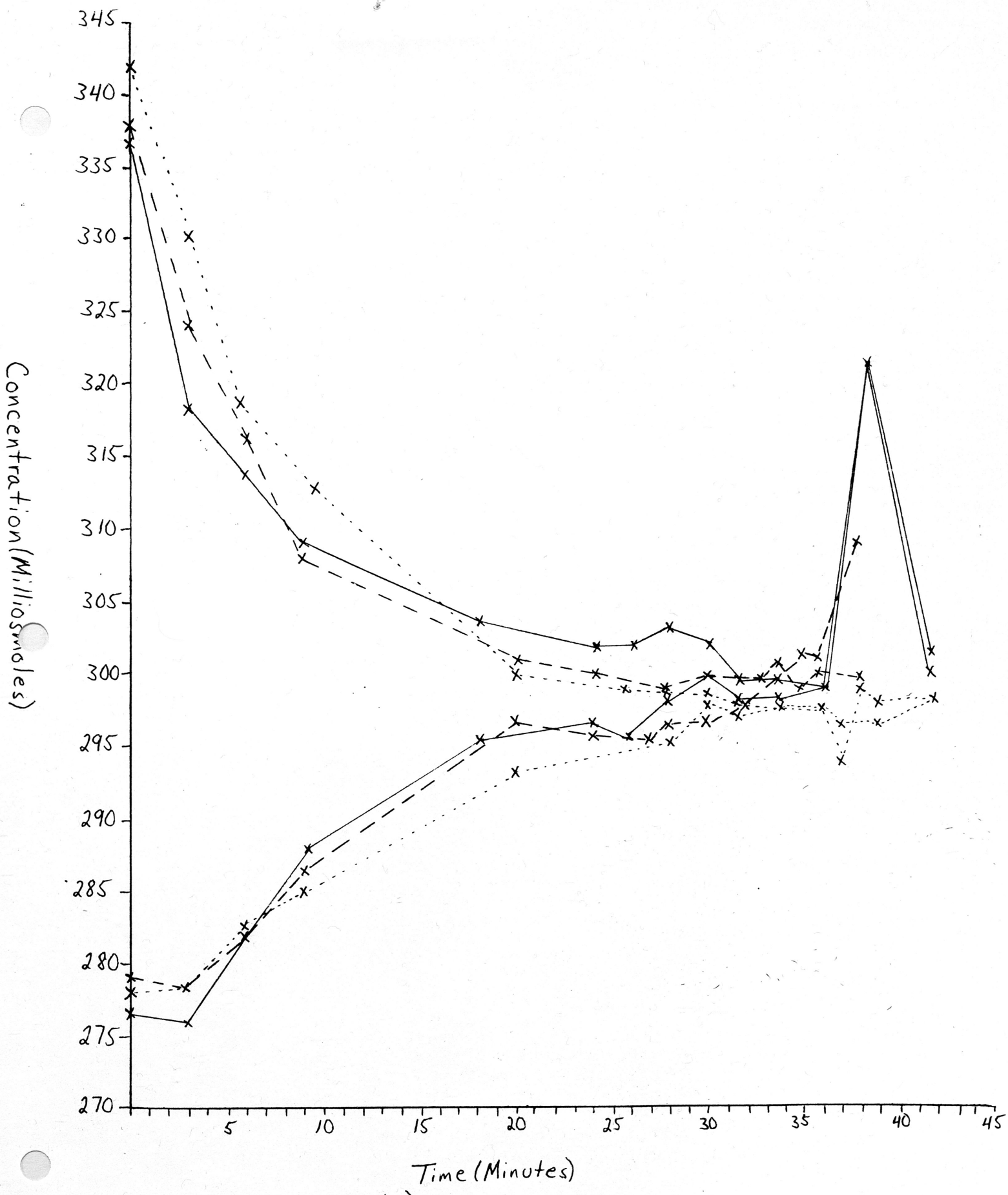
Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	337	280
1		
2		
3		
4	324	284
5		
6		
7		
8	318	290
9		
10		
11		
12	311	292
13		
14		
15		
16	313	296
17		
18		
19		
20	311	297
21		
22		
23		
24		
25	309	298
26		
27		
28		
29		
30	307	300
31		
32		
33		
34		
35		
36	305	303
37		
38		
39		
40		
41		
42	304	303

Experiment 18- 35 Reuses

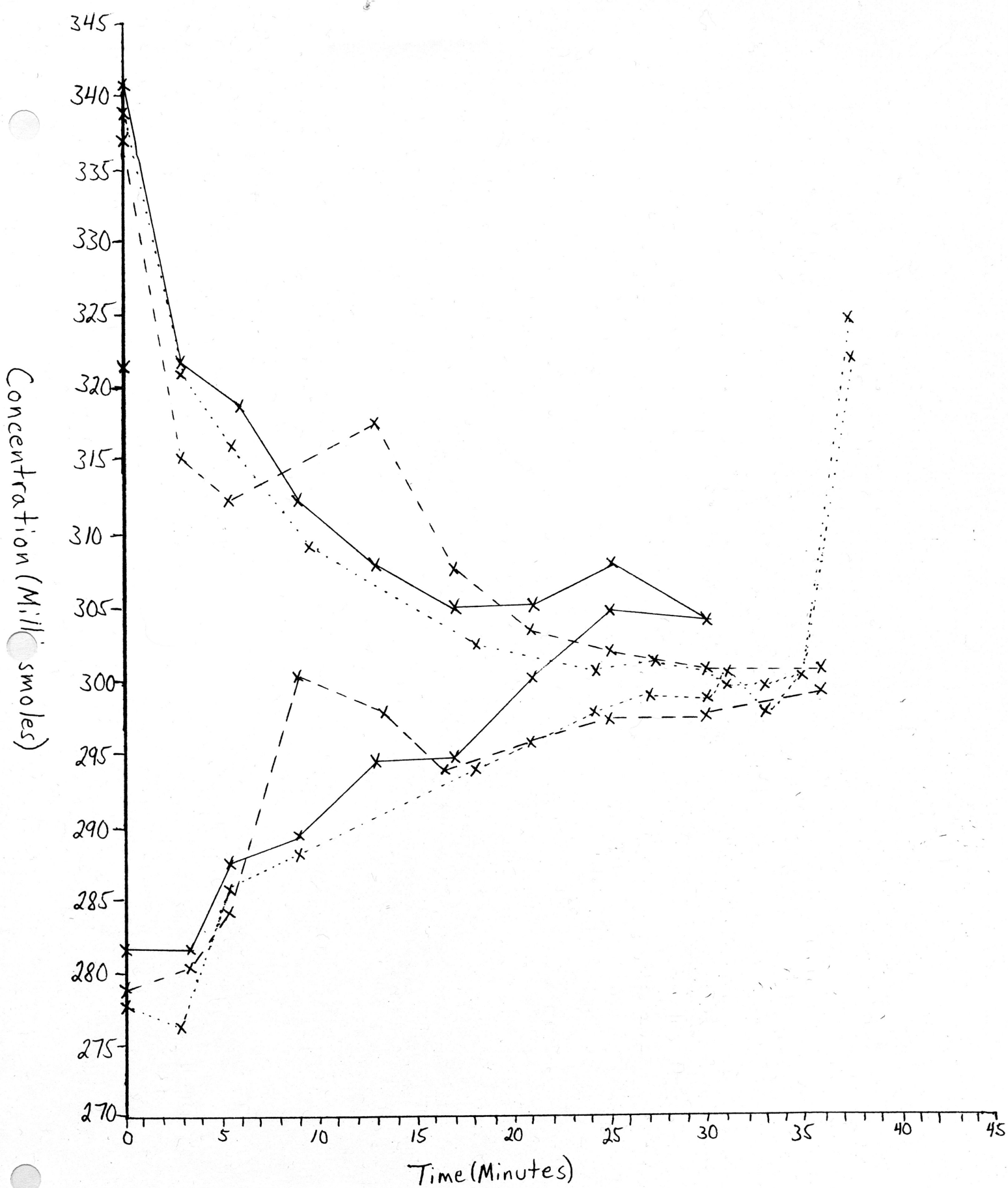
Time (Minutes)	Blood Solution Concentration (Milliosmoles)	Dialysate Solution Concentration (Milliosmoles)
0	347	288
1		
2		
3	330	287
4		
5		
6	320	301
7		
8		
9		
10	313	311
11		
12		
13		
14		
15	309	300
16		
17		
18		
19		
20	308	302
21		
22		
23		
24		
25		
26		
27	306	304
28		
29		
30		
31		
32		
33	306	304

Appendix B
(Graphs of Concentration Versus Time)

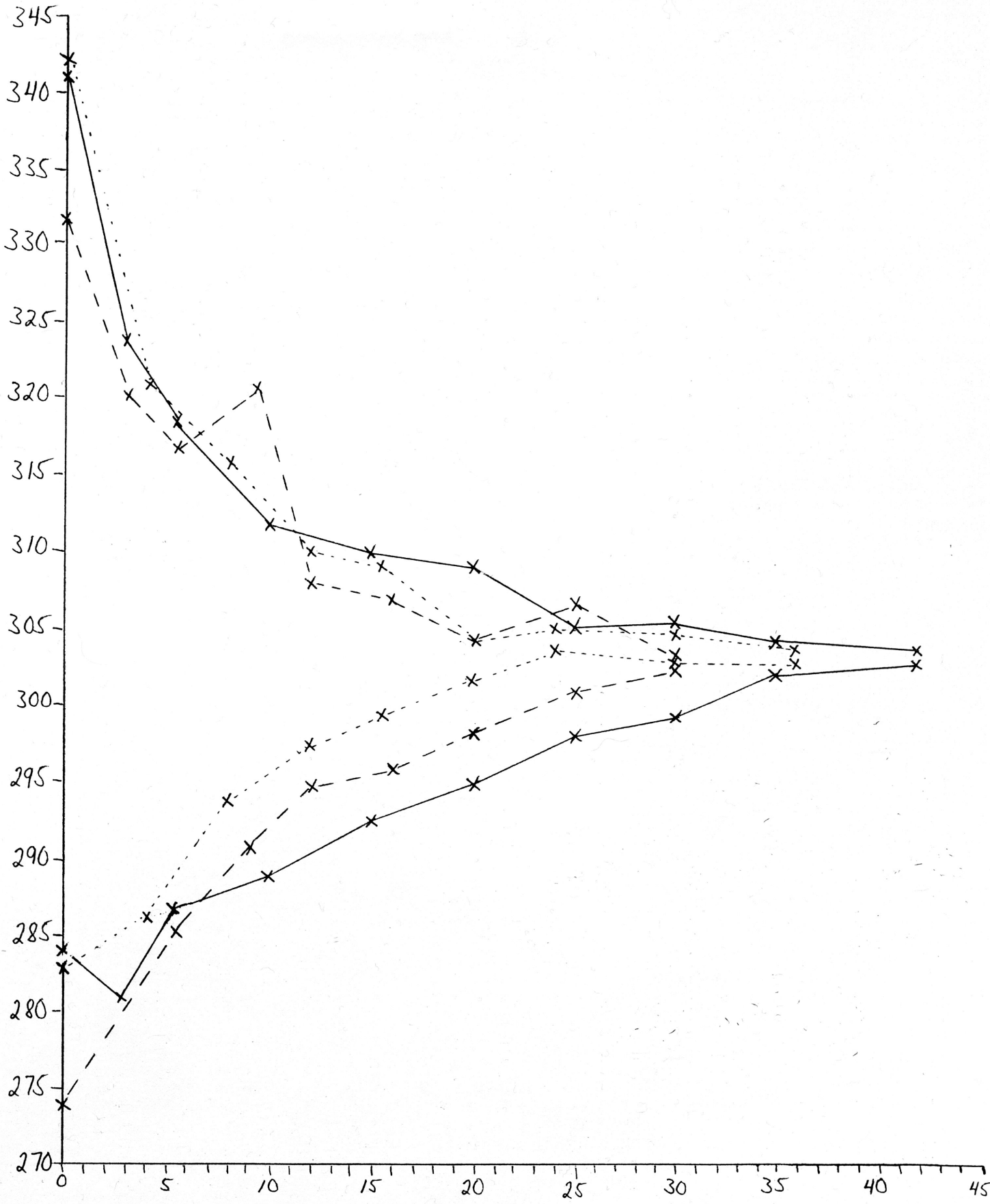

350
345
340
335
330
325
320
315
310
305
300
295
290
285
280
275
0
5
10
15
20
25
30
35
40
45
Concentration (Milliosmoles)
Time (Minutes)
3 Reuses —— (Expt. 1)
5 Reuses - - - (Expt. 2)
6 Reuses ····· (Expt. 3)



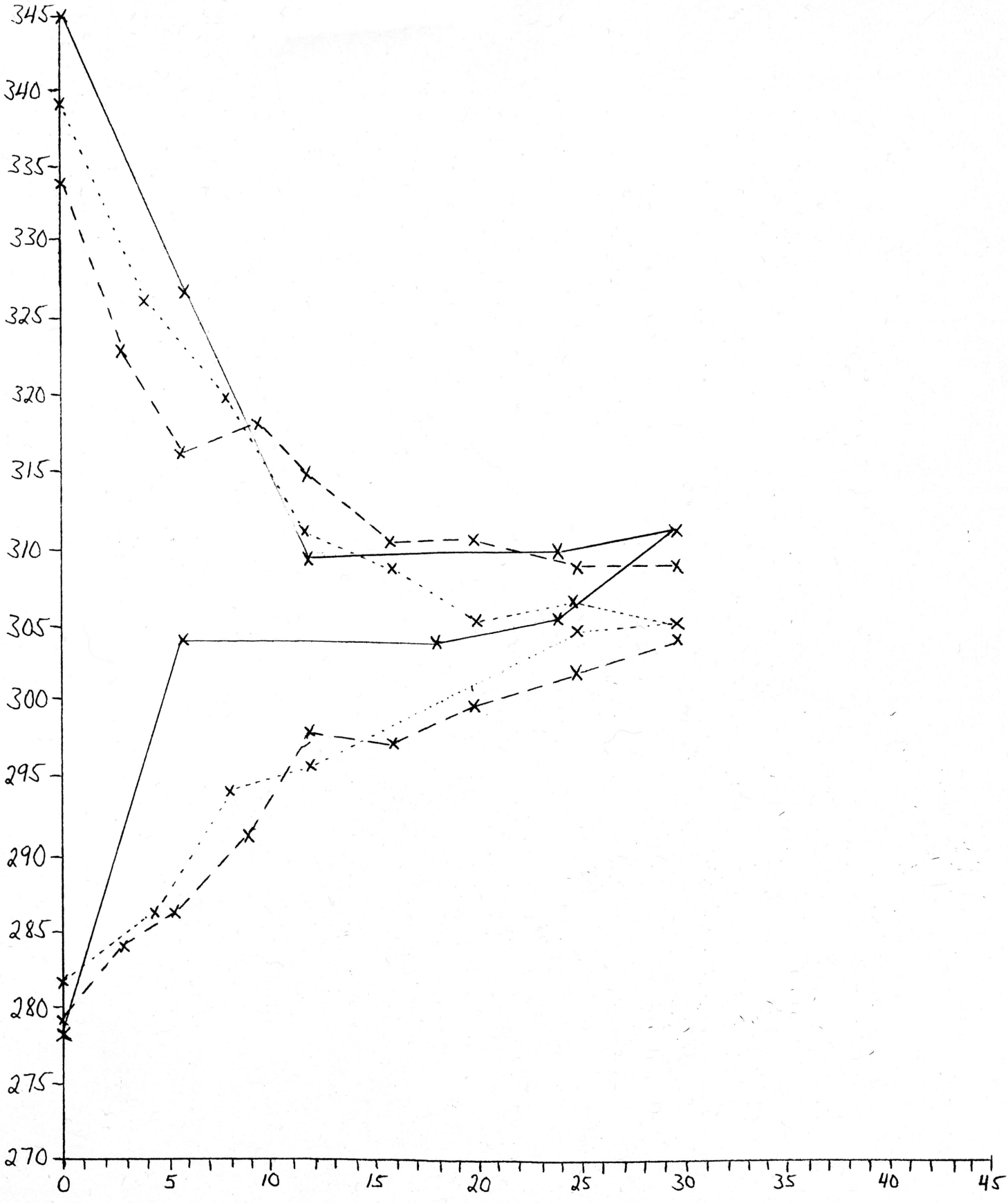
6 Reuses —— (Expt. 4)
7 Reuses – – – (Expt. 5)
10 Reuses · · · · · (Expt. 6)



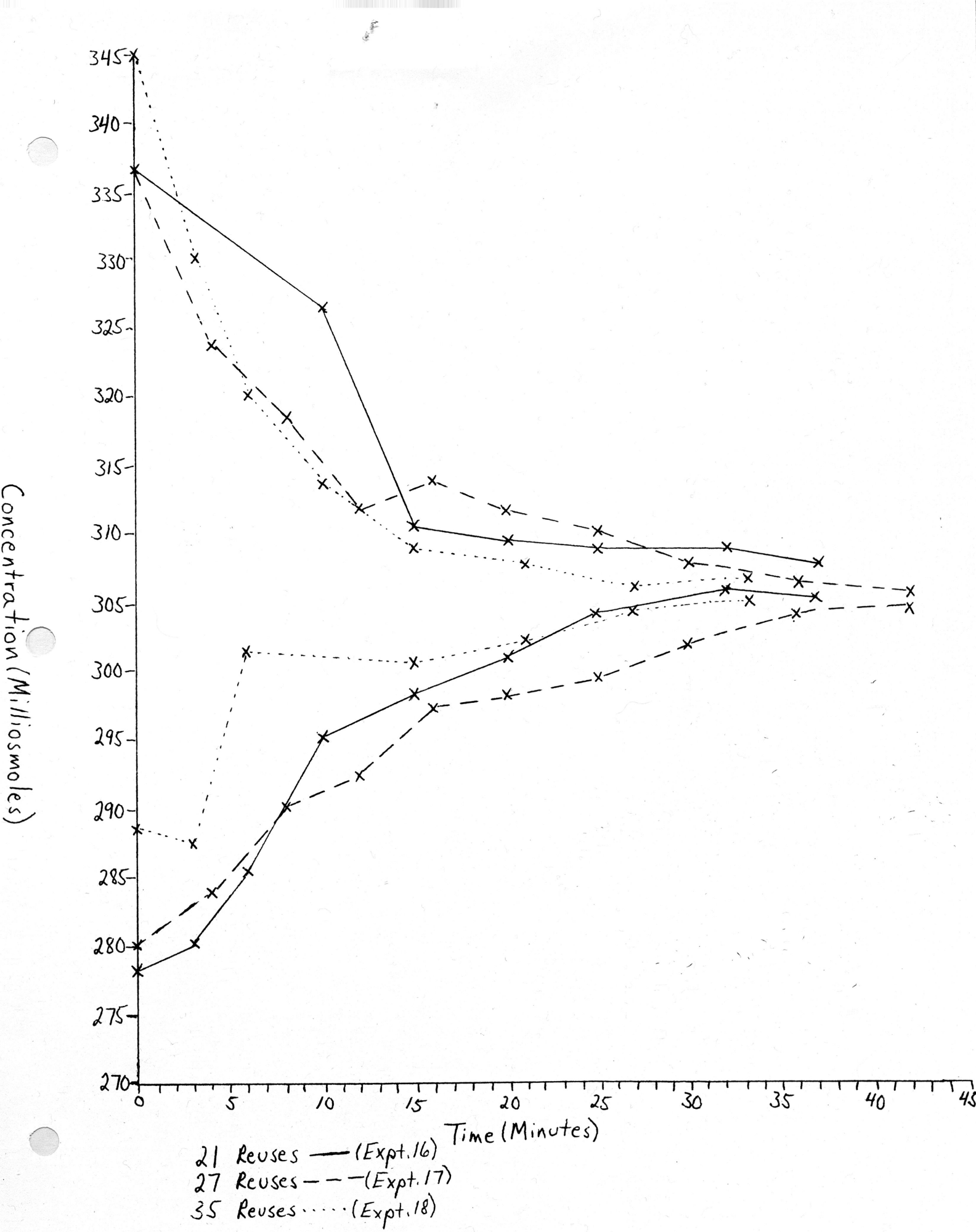
10 Reuses —— (Expt. 7)
10 Reuses - - - - (Expt. 8)
10 Reuses ····· (Expt. 9)



10 Reuses —— (Expt. 10)
11 Reuses - - - (Expt. 11)
13 Reuses · · · · (Expt. 12)



14 Reuses —— (Expt. 13)
18 Reuses - - - (Expt. 14)
19 Reuses ····· (Expt. 15)


345
340
335
330
325
320
315
310
305
300
295
290
285
280
275
270
0
5
10
15
20
25
30
35
40
45
Concentration (Milliosmoles)
Time (Minutes)
21 Reuses —— (Expt. 16)
27 Reuses – – – (Expt. 17)
35 Reuses ····· (Expt. 18)