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Effect of dialysate composition on intercompartmental fluid shift

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Effect of dialysate composition on intercompartmental fluid shift. Effect of dialysate composition on intercompartmental fluid shift and hemodynamics was studied in 12 patients during 1.5 or 2 hours of hemodialysis without net ultrafiltration, using high (H;Na 154 mmol/liter), normal (N;Na 140 mmol/liter) or low (L:Na 126 mmol/liter) concentration dialysate. H dialysate was associated with a small (0.9%) increase in blood volume, a larger increase in plasma volume and a decrease in erythrocyte volume. L dialysate resulted in a 2.3% decrease in blood volume, a larger decrease in plasma volume and an increase in erythrocyte volume. N dialysate gave results which were intermediately between the other two dialysis conditions. There was no difference in the post-dialysis mean arterial pressure between the groups, although heart rate increased more during H dialysis than during the other two conditions. Change in blood and erythrocyte volume correlated significantly with change in plasma Na concentration and osmolality, but not with change in plasma urea concentration. We conclude that dialysate composition affects the movement of water into and out of the plasma and erythrocytes in a manner that can be accounted for by altered plasma concentrations of osmotically active substances.

Several studies have shown that the frequency and severity of dialysis related symptoms, such as hypotension and cramps, can be reduced by raising the dialysate sodium (D_{Na}) concentration [1–4]. This is believed to result, at least in part, from more efficient plasma refilling consequent upon an elevation of plasma osmolality (P_{Osm}) which promotes mobilization of fluid from the extravascular into the vascular space. Studies during hemodialysis, with and without net fluid removal, give some support to this concept but have, to date, been less than satisfactory in their design and execution and have employed methods for measuring change in fluid compartment volumes which are open to criticism. It is not, therefore, surprising that confusing results have been published as to the presence and extent of change in blood volume (BV) when D_{Na} has been varied from low to high concentration. For example, no change in BV was found in one study when D_{Na} was changed from 133 to 140 mmol/liter [1] while in another low D_{Na} was associated with a significant decrease in plasma volume (PV) while high D_{Na} had an insignificant effect [4].

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To avoid these criticisms we have studied patients during hemodialysis without net fluid removal and have employed methods to measure change in blood and plasma volumes which do not require the use of radioisotopes. Our results confirm that during hemodialysis without net convective transport of fluid across the dialysis membrane, change in D_{Na} affects intravascular volume in a qualitatively predictable manner.

Methods

Patients

Six male and six female, stable hemodialyis patients, median age 49 years (range 23 to 59), were studied after having given informed consent. Median time on hemodialysis was five months (range 1 to 118). One patient had taken 10 mg of prednisolone for three months but no other took medication known to affect the cardiovascular system. Patients were neither fluid overloaded nor depleted and passed less than 400 ml of urine per day. Primary renal disease was polycystic kidney disease (3 patients), glomerulonephritis (2) systemic lupus erythematosis (2), atrophic pyelonephritis (2), hypertensive nephropathy (1), polyarteritis (1) and congenitally small single kidney (1).

Dialysis conditions

Patients underwent conventional twin needle dialysis on a 1 m^2 hollow–fiber cuprophane dialyzer (Dylade C1) with extracorporeal blood flow rates between 200 and 250 ml/min and dialysate flow of 500 ml/min. Anticoagulation was by routine systemic heparinization. The automatic supply unit (Dylade Series E) used employs volumetric control of ultrafiltration which allows dialysis to take place without net removal of fluid. The proportioning pump was calibrated so that dialysis could proceed against low (L, D_{Na} 126 mmol/liter), normal (N, D_{Na} 140 mmol/liter), or high (H, D_{Na} 154 mmol/liter) concentration dialysate. N concentration dialysate also contained: K 1.43 mmol/liter, Ca 1.73 mmol/liter, Mg 0.54 mmol/liter, acetate 37.4 mmol/liter, Cl 108 mmol/liter, and dextrose 1.92 g/liter. Alterations in dialysate Na concentration result in a proportional change in the concentration of all these substances.

Study design

Each patient was studied during three consecutive dialyses at two to three day intervals, and a different concentration dialy-

sate was used on each occasion. They refrained from eating, drinking, or smoking and remained supine from one hour before connection to the extracorporeal circuit and throughout the study. Patients were connected to the circuit after the priming volume of saline was discarded. There followed a 30-minute equilibration period during which blood but not dialysate circulated, and neither dialysis nor ultrafiltration took place. Blood was then withdrawn from the "arterial" line for estimation of water content (3 ml) as well as for plasma osmolality(P_{Osm}), urea(P_{urea}) and electrolytes. Further samples were taken from patients 8 to 12 for measurement of hemoglobin concentration (Hb; 1 ml) hematocrit (Hct; 1 ml), plasma oncotic pressure (P_{onc}) and plasma water content (C_{PW}). Plasma samples were obtained by decanting the plasma from the red cell layer after blood had been standing for 20 minutes in sealed sterile containers. The red cells were then returned to the patient. Dialysis with no net ultrafiltration was then commenced. Repeat blood and plasma samples were taken after 90 minutes. The study period was extended to two hours for patients 8 to 12, after which time further blood and plasma samples were taken.

Measurements

Body weight was recorded continuously with bed scales (Datex) and the study repeated on a subsequent day if body weight varied more than 100 grams during the experiment. Systolic and diastolic blood pressure (BP) and heart rate (HR) were monitored at five minute intervals from the start of the equilibration period using the Critikon Vital Signs Monitor, which measures BP oscillometrically and displays the results digitally. Mean arterial pressure (MAP) was calculated as 1/3 systolic + 2/3 diastolic BP. Mean BP and HR measurements obtained during the last 15 minutes of the equilibration and experimental dialysis periods were used for analysis of results. Nadir MAP was the lowest MAP recorded at any stage during the experimental dialysis period.

Plasma and dialysate urea and electrolytes were measured by autoanalyzer and osmolality by freezing point depression (Advanced Instruments, Inc.). Hct was taken as the mean of six to eight readings obtained using a direct microhematocrit method after centrifugation for ten minutes and correction for 1.8% trapped plasma [5]. Hb was measured on a Coulter-S counter (Coulter Electronics, Hileah, Florida, USA) and Mean Corpuscular Hemoglobin Concentration (MCHC) calculated as Hb/Hct. P_{onc} was measured with an oncometer incorporating an Amicon PM-30 membrane (Amicon, Lexington, Massachusetts, USA).

Blood water content (C_{BW}). After collection into heparinized tubes blood was mixed for at least 30 minutes. It was then drawn up into a platform mounted syringe pipette and aliquots of approximately 0.6 ml delivered into wide-necked glass bottles. The syringe pipette was calibrated using distilled water so that the true volume of each sample could be obtained after weighing. C_{BW} was determined by weighing the bottle of blood before and after drying in an oven at 105° for 12 hours and expressed as gH_2O/ml blood. The mean of three readings of C_{BW} obtained from each sample was used.

Blood volume (BV) change. Assuming that BV changes only as a result of water shift and that the fraction of the total blood volume removed for sampling is insignificant, the volume of blood at time t (BV_t) expressed as a proportion of the volume at time 0 (BV_0) is given by:

$$\frac{BV_t}{BV_o} = \frac{(1 - C_{BWo})}{(1 - C_{BWt})} \quad (1)$$

where C_{BW0} and C_{BWt} are values of C_{BW} at time 0 and t, respectively, (**Appendix**). The accuracy with which BV change in vitro can be monitored by serial blood water estimations is discussed by Greenwood, Aldridge and Cattell [6].

Plasma water content (C_{PW}) and plasma volume (PV) change. C_{PW} was measured in a similar manner to C_{BW} by weighing a standard aliquot of plasma before and after it was dried in an oven for 12 hours. An expression relating PV at time t (PV_t) to its starting value (PV_0) can be derived making the same assumptions as for the calculation of relative BV:

$$\frac{PV_t}{PV_o} = \frac{(1 - C_{PWo})}{(1 - C_{PWt})} \quad (2)$$

where $_0$ and $_t$ refer to values at time 0 and t, respectively.

Change in erythrocyte volume (EV). This was calculated from change in MCHC. Since total mass of hemoglobin = MCHC × EV, for hemoglobin mass balance

$$MCHC_o \times EV_o = MCHC_t \times EV_t$$

or

$$\frac{EV_t}{EV_o} = \frac{MCHC_o}{MCHC_t} \quad (3)$$

where $_0$ and $_t$ refer to values at time 0 and t, respectively.

Erythrocyte water content (C_{EW}). If it is assumed that the water in blood is contained in plasma and red cells alone, then the mass of water contained in whole blood, ($BV \cdot C_{BW}$) is given by:

$$BV \cdot C_{BW} = PV \cdot C_{PW} + EV \cdot C_{EW}$$

$$= BV \cdot (1 - Hct) \cdot C_{PW} + BV \cdot Hct \cdot C_{EW}$$

or

$$C_{EW} = \frac{C_{BW} - C_{PW} + C_{PW} \cdot Hct}{Hct} \quad (4)$$

Statistics

Analysis of variance (F ratio) was used for the initial comparison of group means under the three experimental conditions, with subsequent between group comparisons carried out using Student's *t*-test for paired data. Correlation coefficients (*r* values) were calculated by linear regression.

Results

Mean biochemical and hemodynamic data for the 12 patients before dialysis with H, N, and L concentration dialysate are shown in Table 1. There were no significant differences before treatment in C_{BW}, P_{Osm}, P_{urea}, P_{Na}, BP or HR. Post-dialysis values are displayed in Table 2. The three dialysates resulted in significantly different values for C_{BW}, P_{Osm} and P_{Na}, but not P_{urea} which fell a similar amount under the three experimental conditions.

On average MAP fell significantly (5.5 mm Hg, $t = 2.32$, $P < 0.025$) during experimental dialysis. However there was no significant difference between the post-dialysis BP (systolic, diastolic or MAP) resulting from the use of the different

Table 1. Mean (SD) predialysis biochemical and hemodynamic data, $N = 12$

	Dialysate concentration			Between groups	
	H	N	L	F ratio	*P*
C_{BW} *g/ml*	0.8841 (0.0104)	0.8832 (0.0122)	0.8821 (0.004)	0.0	NS
P_{Osm} *mOsm/kg*	302.4 (7.9)	303.5 (9.0)	304.0 (8.0)	0.1	NS
P_{Urea} *mmol/liter*	22.1 (5.5)	22.4 (8.1)	22.7 (5.7)	0.0	NS
P_{Na} *mmol/liter*	138.9 (2.0)	139.3 (2.2)	139.3 (2.2)	0.2	NS
BP *mm Hg*					
systolic	154.1 (21.0)	148.2 (19.1)	153.4 (20.7)	1.0	NS
diastolic	89.7 (13.9)	86.3 (12.3)	89.3 (11.7)	0.9	NS
MAP	111.1 (14.8)	106.9 (11.9)	110.7 (12.5)	1.0	NS
HR min^{-1}	76.3 (14.4)	80.9 (19.7)	79.1 (14.2)	1.3	NS

Table 2. Mean (SD) biochemical and hemodynamic data after 1.5 hours experimental dialysis, $N = 12$

	Dialysate concentration			Between groups	
	H	N	L	F ratio	*P*
C_{BW} *g/ml*	0.8851 (0.0109)	0.8826 (0.0127)	0.8793 (0.0110)	33.0	<0.001
P_{Osm} *mOsm/kg*	301.7 (6.4)	293.3 (7.0)	283.1 (6.6)	25.1	<0.001
P_{Urea} *mmol/liter*	14.2 (3.7)	14.4 (4.9)	14.5 (3.5)	0.0	NS
P_{Na} *mmol/liter*	143.8 (1.5)	139.3 (1.6)	134.7 (2.2)	106.7	<0.001
BP *mm Hg*					
systolic	152.0 (25.0)	145.4 (23.1)	148.1 (21.3)	0.90	NS
diastolic	82.1 (13.5)	81.1 (12.8)	85.4 (12.2)	1.40	NS
MAP	105.2 (15.2)	102.0 (14.9)	105.2 (15.2)	1.20	NS
Nadir MAP	97.6 (14.4)	97.1 (11.9)	101.0 (11.2)	1.50	NS
HR min^{-1}	89.8 (16.7)	89.4 (18.6)	84.2 (15.4)	4.54	<0.05

concentration dialysates. Similarly, there was no difference between the nadir MAPs.

Post-dialysis HR varied with dialysate concentration as did dialysis–induced change in HR ($F = 10.63$, $P < 0.001$). The increase in HR following H concentration dialysis (13.5 min^{-1}) was significantly greater than the 8.5 min^{-1} increment obtained with N ($t = 2.48$, $P < 0.05$) or the 5.1 min^{-1} increase observed with L concentration dialysis ($t = 6.63$, $P < 0.001$). There was no significant difference between the HR change observed with L and N dialysate ($t = 1.6$, $P > 0.1$).

C_{BW} after 90 minutes dialysis differed with dialysate concentration as did the percent of change in BV ($F = 10.55$, $P < 0.001$; Fig. 1). BV increased an average 0.9% during H concentration dialysis and decreased 0.5% and 2.3% during N and L concentration dialysis, respectively. There were significant differences between BV response to H and N concentration dialysate ($t = 1.97$, $P < 0.05$) and between N and L ($t = 2.62$, $P < 0.025$).

Percentage change in BV correlated significantly with the percent of change in P_{Osm} ($r = 0.53$, $P < 0.001$; Fig. 2) and P_{Na} ($r = 0.52$, $P < 0.001$; Fig. 3), but not with change in P_{urea} ($r = -0.15$, $P > 0.1$).

Results from the extended study are summarized in Table 3. Change in EV calculated from change in MCHC correlated closely with change in C_{EW} ($r = 0.89$, $P < 0.001$; change in EV = 0.0 + 2.22 change in C_{EW}). Because of the small number of patients involved [5], statistical analysis was not carried out on between group differences. H concentration dialysis is associated with an increase in BV, a greater increase in PV and a decrease in EV. L concentration dialysate causes a decrease in BV, a bigger decrease in PV and an increase in EV. N concentration dialysate gives results intermediate between those obtained using H and L.

There was a highly significant negative correlation between the percent change of P_{onc} and percent change in C_{PW} with increases in C_{PW} being associated with decreases in P_{onc} ($r = -0.89$, $P < 0.001$, Fig. 4).

The percent change in EV correlated with percent change in P_{NA} ($r = -0.81$, $P < 0.001$; Fig. 5) and P_{Osm} ($r = -0.81$, $P < 0.001$; Fig. 6) but not with change in P_{urea} ($r = -0.15$, $P > 0.1$). A rise in P_{Osm} or P_{Na} is associated with shrinkage of erythrocytes, while a decrease in these variables is associated with erythrocyte swelling.

Discussion

Hypotension occurs commonly during hemodialysis and has been attributed to both reduction in BV [7] and to hemodynamic changes, such as a failure of peripheral vascular resistance to increase during dialysis [8] or depression of cardiac contractility [9]. Reduction in BV can be induced by removal of plasma water in excess of plasma refilling from extravascular sites. The main driving force for plasma refilling during dialysis and ultrafiltration is elevation of plasma osmotic pressure. Methods designed to increase P_{Osm} during hemodialysis and ultrafiltration such as increasing D_{Na} [2, 3], administration of Dextran [7] or mannitol [10] have all been used successfully to reduce some dialysis related symptoms.

Studies examining intercompartmental fluid shifts during hemodialysis and ultrafiltration under differing conditions of D_{Na} concentrations are difficult to perform. For fair comparison

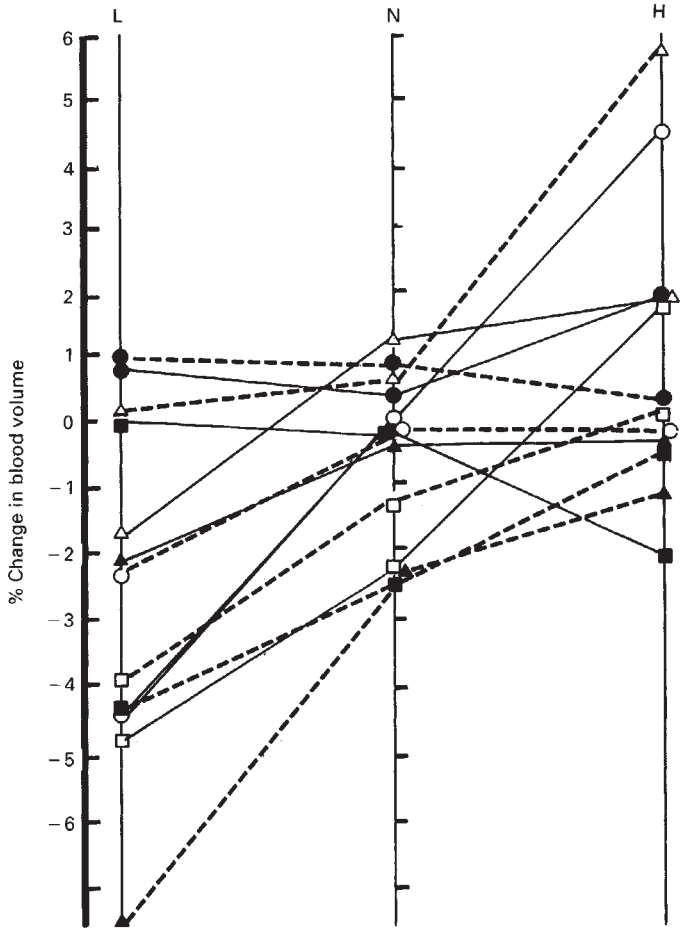

Fig. 1. *Percent change in blood volume (BV) after 1.5 hours treatment with high (H), Normal (N) and Low (L) concentration dialysate.* Different symbols refer to data obtained from individual subjects, N = 12.

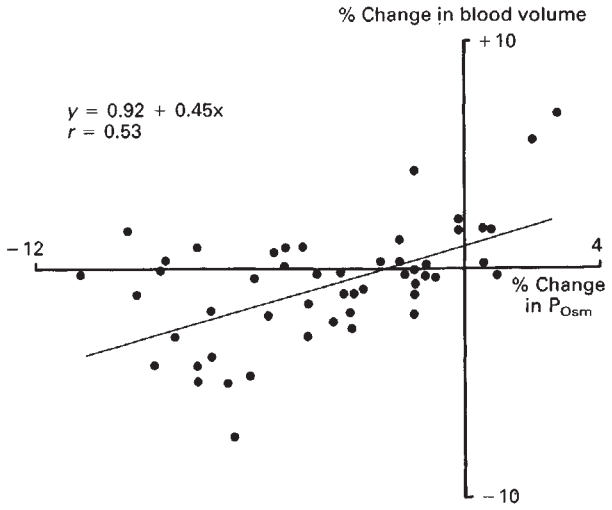

Fig. 2. *Relationship between percent change in plasma osmolality (P_{Osm}) and blood volume (BV).* Data from 1.5 and 2 hours. N = 12.

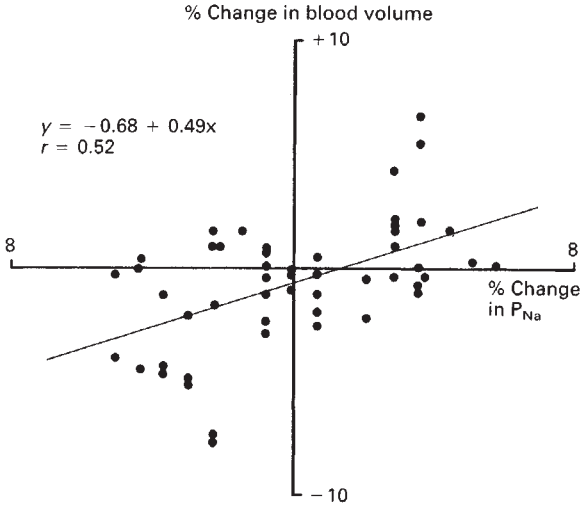

Fig. 3. *Relationship between percent change in plasma Na(P_{Na}) and blood volume (BV).* Data from 1.5 and 2 hours. N = 12.

it is essential that identical amounts of fluid are removed under the different experimental conditions. Examination of published results [4, 11, 12] indicates that this has not always been achieved. In some cases [11, 12] intravenous fluids were administered during the study in an attempt to ensure that identical amounts of fluid were removed under the different experimental conditions, but this in itself must prejudice the interpretation of results. For this reason we chose to study the effect of varying dialysate concentration on circulating blood and plasma volume when there was no net removal of fluid which we confirmed by body weight changes of less than 100 grams during the experiment.

A second problem with previous studies has been the doubtful validity of using radioisotope techniques to measure PV and/or extracellular fluid volume before and after dialysis and ultrafiltration [4, 11–13]. For this to be valid there must be no transcellular fluid shifts occurring in the post-dialysis period [12]. However, it has clearly been shown that plasma refilling continues for some hours after ultrafiltration has ceased [14]. The inappropriate use of isotopic dilution methods in the immediate post-dialysis period could account for apparently anomalous results, such as high D_{Na} with zero ultrafiltration causing a 1350 ml increase in extracellular fluid (calculated from pre- and post-dialysis measurement of $Na_2{}^{35}SO_4$ space), yet only a 30 ml increment in PV (calculated from change in serum albumin concentration) [4].

A further potential methodological error can arise where measurement of change in BV or PV is based on change in Hct. The latter can only be used if it is certain that there has been no change in EV. We have shown previously [15] that there is change in EV under changing conditions of plasma sodium concentration. This is in conflict with previous claims [3, 16] that erythrocyte volume does not change during hemodialysis with low as opposed to high D_{Na}.

The present study was designed to avoid these various problems. To concentrate on the effect of hemodialysis against low, normal, and high D_{Na} on circulating blood and plasma volume we chose to eliminate fluid removal by ultrafiltration,

Table 3. Percent alteration in blood volume (BV), plasma volume (PV), erythrocyte volume (EV) and oncotic pressure (P_{onc}) after 1.5 and 2 hours experimental dialysis, $N = 5$

Dialysate concentration	1.5 hours % change in				2 hours % change in			
	BV	PV	EV	P_{onc}	BV	PV	EV	P_{onc}
H	+1.2	+4.3	−4.0	−3.9	+2.0	+3.6	−3.9	−5.0
N	−0.8	−0.6	+0.3	+0.7	−1.1	−1.5	+0.4	+1.2
L	−3.0	−5.2	+3.1	+7.5	−3.2	−6.7	+1.9	+8.8

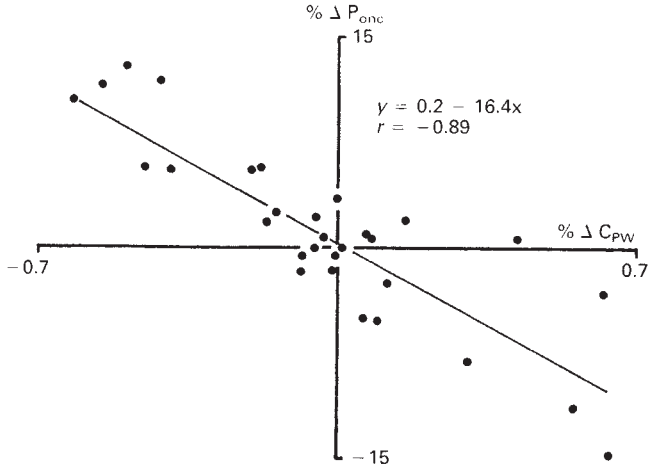

Fig. 4. *Relationship between percent change in plasma water (C_{PW}) and oncotic pressure (P_{onc}). $N = 5$.* Data from 1.5 and 2 hours.

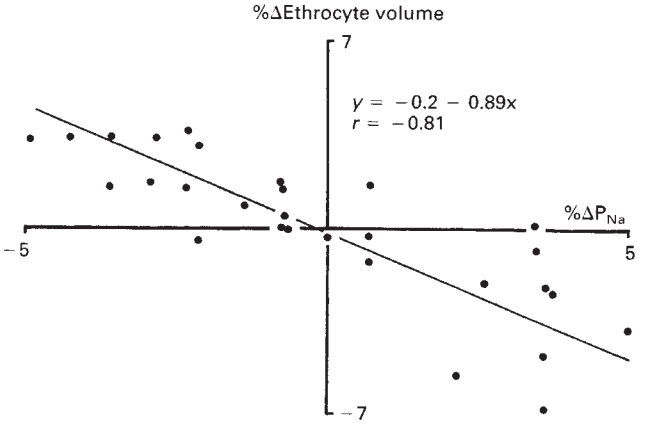

Fig. 5. *Relationship between % change in erythrocyte volume (EV) and plasma Na (P_{Na}). $N = 5$.* Data from 1.5 and 2 hours.

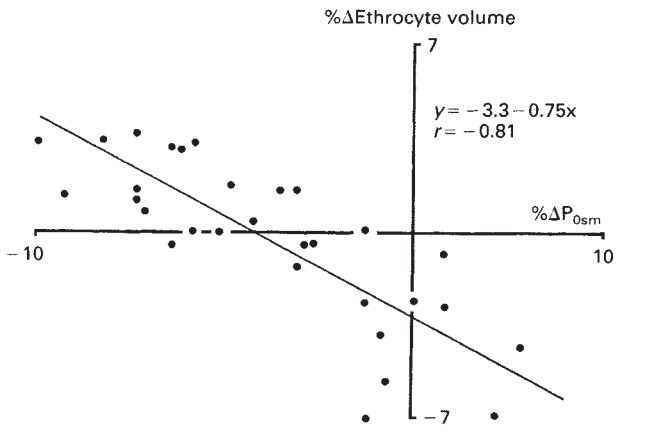

Fig. 6. *Relationship between percent change in erythrocyte volume (EV) and plasma osmolality (P_{Osm}). $N = 5$.* Data from 1.5 and 2 hours.

thus avoiding difficulties in controlling exactly the amount removed and the need for intravenous infusion of fluid during the studies. We have also used a greater difference in D_{Na} (10%) than other workers.

Our results show that hemodialysis against high D_{Na} results in a rise in blood and plasma water concentrations whereas their values fall during haemodialysis against low D_{Na}. Assuming that change in circulating BV relates purely to change in water content, we found that BV increases significantly during hemodialysis against high D_{Na} and decreases to a greater degree with low D_{Na}. These changes correlate significantly with change in P_{Osm} and P_{Na}, but not with change in P_{urea} concentration.

A possible criticism of the use of blood and plasma water concentration to study changes in their respective volumes is our assumption that there is no change in the mass of circulating erythrocytes or plasma solids during dialysis which would invalidate the use of equations (1) and (2).

With respect to change in circulating red cell-mass, due to change in the ratio of peripheral to whole blood hematocrit, addition or removal of erythrocytes from the peripheral circulation would alter the hematocrit. This could not, however, alter the MCHC save in the unusual situation of having a dimorphic population of erythrocytes which have differing levels of hemoglobination—one population being selectively added or removed—or where there is acute intravascular hemolysis. Neither of these situations applied to our patients. If, therefore, there is a change in peripheral blood to whole body hematocrit, there is still nevertheless a change in erythrocyte volume. That this is due to change in erythrocyte water content is supported by the close correlation between change in EV and C_{EW}. Coexistent change in the ratio of peripheral to whole blood hematocrit cannot be excluded, but such a change does not invalidate our observation of change in erythrocyte water as a factor affecting change in whole blood volume.

With respect to any change in the mass of plasma solids, such a change would certainly affect C_{PW} and hence the calculated change in plasma volume. The mass of non-protein, small molecular weight compounds undoubtedly changes. However, the close negative correlation between change in P_{onc} and C_{PW}

indicates that any change in the mass of non-protein, small molecular weight compounds has an insignificant effect on C_{PW}. Much more important would be any change in the mass of circulating protein. We know of no data which indicates ingress or egress of plasma proteins (and especially plasma albumin) into or out of the circulation during dialysis, and indeed many previous workers have used change in plasma protein concentration to reflect change in plasma volume during dialysis experiments [1, 11]. Given our objection to the use of isotope studies, it is not possible to confirm or exclude any shift in plasma proteins. Should there be a primary change in circulating protein mass, the expected change in C_{PW} and P_{onc} would be different. Thus, ingress or plasma protein should raise oncotic pressure and attract water into the circulating plasma while egress would do the reverse. The effect of this would be to diminish shifts in water due to change in plasma osmolality. While such a possibility cannot be refuted, our results indicate that the major shift of water is in the direction expected from change in the osmotic effect of sodium chloride.

The finding of a decrease in EV following high sodium dialysis and an increase with low sodium dialysis results in significant changes in the ratio of red cell volume to whole blood volume under the different conditions. Failure to identify this change in red cell volume invalidates the use of Hct in calculating change in PV [15].

All of these findings confirm the theoretical expectation that increase in P_{Osm} will result in a movement of water into the vascular compartment while the reverse occurs with a decrease in P_{Osm}. The significant correlation between fluid shifts and change in P_{Na} but not with P_{urea} support the belief [12] that alteration of P_{urea} generates little osmotic gradient because of its mobility between fluid compartments. It is not possible from these studies to define movement of water between extra- and intracellular compartments. The changes in erythrocyte volume do, however, support the notion that Na induces an osmotic gradient resulting in change in the ratio of extra- to intracellular water.

Caution is necessary in extrapolation of these results to combined hemodialysis and ultrafiltration. While the same osmotic forces may be expected, the size of fluid shifts will be conditioned by the rate of fluid removal from the vascular compartment by ultrafiltration. In addition, an ultrafiltration induced increase in P_{onc} will to some extent affect fluid shifts as may change in capillary hydrostatic pressure.

There was no difference in post-dialysis BP between the three conditions, despite the fact that HR and BV increased more with H conductivity dialysis than it did under the other two conditions. In some [1], but not all [4] studies, BP has been reported to fall less with high D_{Na} than with low under conditions of zero net ultrafiltration. However, the changes in BV are small and it is not surprising that when they are unaccompanied by large reductions in BV induced by ultrafiltration, they do not give rise to different BP responses.

In conclusion, our studies clearly show that dialysate composition affects the movement of water into and out of the plasma and erythrocytes in a manner that can be accounted for on the basis of altered plasma concentrations of osmotically active substances.

Appendix

V_0 and C_{BW0} are the starting blood volume and blood water concentrations respectively, and V_t and C_{BWt} the values after ultrafiltration of water; V_{UF} is the volume of water ultrafiltered; V_{BT} and C_{BWt} are the volume and water content of a blood sample taken at time T during ultrafiltration.

Assuming blood has a specific gravity of approximately 1.0 and there are multiple blood samples:

$$V_o - V_t = V_{UF} + \sum_{T=o}^{T=t} V_{BT}$$

and, for water mass balance,

$$V_o \cdot C_{BWo} - V_t \cdot C_{BWt} = V_{UF} + \sum_{T=o}^{T=t} V_{BT} \cdot C_{BWT}$$

Substituting for V_{UF} for Equation (1),

$$V_o \cdot C_{BWo} - V_t \cdot C_{BWt} = V_o - V_t - \sum_{T=o}^{T=t} V_{BT} + \sum_{T=o}^{T=t} V_{BT} \cdot C_{BWT}$$

$$V_t = \frac{V_o(1 - C_{BWo})}{(1 - C_{BWt})} - \sum_{T=o}^{T=t} V_{BT} \frac{(1 - C_{BWT})}{(1 - C_{BWt})}$$

If the total volume taken for blood sampling is small,

$$\frac{V_t}{V_o} = \frac{(1 - C_{BWo})}{(1 - C_{BWt})}$$

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References

1. Wehle B, Asaba H, Castenfors J, Gunnarsson B, Bergstrom J: Influence of dialysate composition on cardiovascular function in isovolaemic haemodialysis. *Proc EDTA* 18:153–159, 1981
2. Stewart WK, Fleming LW, Manuel MA: Benefits obtained by the use of high sodium dialysate during maintenance haemodialysis. *Proc EDTA* 9:111–118, 1972
3. Swartz RD, Somermeyer MG, Hsu C-H: Preservation of plasma volume during hemodialysis depends on dialysate osmolality. *Am J Nephrol* 2:189–194, 1982
4. Van Stone JC, Bauer J, Carey J: The effect of dialysate sodium concentration on body fluid compartment volume, plasma renin activity and plasma aldosterone concentration in chronic hemodialysis patients. *Am J Kid Dis* 11:58–64, 1982
5. Pearson TC, Guthrie DL: Trapped plasma in the microhematocrit. *Am J Clin Pathol* 78:770–772, 1982
6. Greenwood RN, Aldridge C, Cattell WR: Serial blood water estimations and in line blood viscometry: The continuous measurement of blood volume during dialysis procedures. *Clin Sci* 66:575–583, 1984
7. Kim KE, Neff M, Cohen B, Somerstein M, Chinitz J, Onesti

G, SWARTZ C: Blood volume changes and hypotension during hemodialysis. *Trans Am Soc Artif Int Organs* 16:508–514, 1970
8. BALDAMUS CA, ERNST W, FREI U, KOCH KM: Sympathetic and hemodynamic response to volume removal during different forms of renal replacement therapy. *Nephron* 31:324–332, 1982
9. AIZAWA Y, OHMORI T, IMAI K, NARA Y, MATSUOKA M, HIRASAWA Y: Depressant action of acetate upon the human cardiovascular system. *Clin Nephrol* 8:477–480, 1977
10. RODRIGO F, SHIDEMAN J, MCHUGH R, BUSELMEIER T, KJELLSTRAND C: Osmolality changes during hemodialysis. Natural history, clinical correlations, and influence of dialysate glucose and intravenous mannitol. *Ann Int Med* 86:554–561, 1977
11. VAN STONE JC, BAUER J, CAREY J: The effect of dialysate sodium concentration on body fluid distribution during hemodialysis. *Trans Am Soc Artif Int Organs* 26:383–386, 1980
12. KIMURA G, VAN STONE JC, BAUER JH, KESHAVIAH PR: A simulation study on transcellular fluid shifts induced by hemodialysis. *Kidney Int* 24:542–548, 1983
13. GARCIA M, CARRERA M, PIERA C, DEULOFEU R, COMPANY X, MA PONS J, MONTOLIU J, SETOAIN J, REVERT L: Changes in body compartments on different types of haemodialysis. *Proc EDTA-ERA* 21:235–240, 1984
14. KOOMANS HA, GEERS AB, DORHOUT MEES EJ: Plasma volume recovery after ultrafiltration in patients with chronic renal failure. *Kidney Int* 26:848–854, 1984
15. FLEMING SJ, CATTELL WR: Red cell volume and plasma sodium. (letter) Nephron 41:126, 1985
16. HSU CH, SWARTZ RD, SOMERMEYER MG, RAJ A: Bicarbonate hemodialysis: Influence on plasma refilling and hemodynamic stability. *Nephron* 38:202–208, 1984