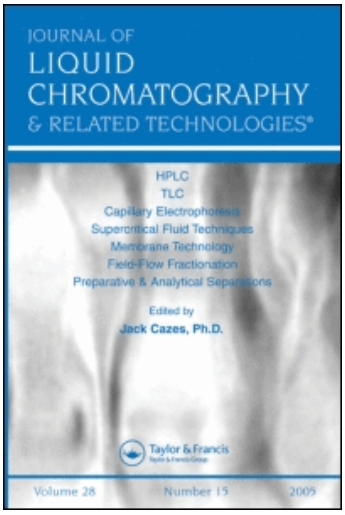

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Evaluation of Sulfopropyl Ion-Exchange Membrane Cartridges for Isolation of Proteins from Bovine Whey

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EVALUATION OF SULFOPROPYL ION-EXCHANGE MEMBRANE CARTRIDGES FOR ISOLATION OF PROTEINS FROM BOVINE WHEY

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ABSTRACT

Separated Cheddar cheese whey was microfiltered to remove residual fat, and adjusted to pH 3 prior to loading into two commercially available membrane cartridges. Minerals and non-protein nitrogen did not bind to the membranes. The mass of protein bound to the membranes increased as the loading volume of whey increased, while the percentage of protein isolated from the whey decreased. Not all of the protein bound to the membranes was eluted using pH 9 buffer. An economic analysis was used for comparison of the cartridges.

INTRODUCTION

Over 100 million pounds of whey protein concentrate (WPC) are used annually as a functional ingredient in bakery, dairy, cereal, beverage and other food

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products [1,2]. WPC is produced by ultrafiltration of whey. However, some undesirable properties of WPC limit its use, such as high lipid and lactose content, low foam formation, and poor foam stability [3]. These undesirable properties are nearly eliminated for whey protein isolate (WPI), which is made by adsorption of whey proteins onto ion-exchange (IEX) beads [3]. However, the cost of WPI is higher than that of WPC, due primarily to higher capital costs for building the IEX plant compared to the ultrafiltration plant [4]. In order to market WPI at a lower cost, either the process efficiency and throughput must be increased, or the capital cost must be decreased.

In commercial WPI manufacturing, whey proteins are adsorbed into IEX beads while whey and beads mix in a large stainless steel tank, followed by draining, washing, and elution of the adsorbed protein. The rate of protein isolation is limited by the rate at which equilibrium between the whey and the IEX beads is approached [5]. For large beads, this rate is slow because of lengthy diffusion times of protein into the IEX beads. Smaller beads decrease the diffusion time. However, these are not used in the commercial process because smaller beads also increase the time for liquid drainage from the tank.

IEX membranes are a new technology designed to overcome the limitations encountered in commercial IEX processes [5,6]. During adsorption, the whey passes through the micron-sized pores of the membrane and the proteins adsorb onto the IEX groups on the membrane surface. Diffusional limitations are negligible because the whey flows by convection through the fine pores of the membrane. Therefore, the IEX membrane process is expected to increase efficiency and throughput compared to the existing IEX processes. Similarities between IEX and ultrafiltration membrane equipment may permit existing WPC manufacturers to convert to WPI production without investing in a new plant. These factors may allow marketing WPI at a lower cost.

In this work, the feasibility of using IEX membranes for WPI production was investigated. Protein production rates, binding capacities, percentage of recovery, and processing parameters were evaluated for two membrane cartridges. The results of this work are useful in establishing the principles underlying the IEX membrane process, and in designing and operating new, more economical whey protein isolation and fractionation processes.

MATERIALS AND METHODS

Microfiltration

Separated (defatted) Cheddar cheese whey (pH 6.2), obtained from Associated Milk Producers, Inc. (Madison, WI) was cooled to 0°C. The whey was recirculated at 0-4°C through a hollow-fiber microfiltration membrane cartridge (model CFP-4-D-4, A/G Technology Corp., Needham, MA) containing polysulfone tubules with a pore size of 0.45 μm. The cartridge membrane area was 0.046 m^2. The pumping system consisted of a Masterflex® high-capacity pump drive (model 7549-30) and pump head (model 7019-00) (Cole Parmer Instrument Co., Chicago, IL). Raw whey (1500 mL) was recirculated until the volume was reduced by 50%. The permeate was adjusted to pH 3.0 using 0.375 M HCl and stored at 4°C. Four separate batches of whey were microfiltered, each having slightly different compositions.

Protein and Mineral Binding Study

Two commercially-available sulfopropyl strong-acid cation-exchange membrane cartridges were used to recover the whey proteins. One cartridge (Productiv® S, model PSC10-SP) was supplied by BPS Separations, Ltd. (Spennymoor, County Durham, U.K.). The unit consisted of a stack of 5 regenerated cellulose membranes. The stack had a bed height of 2 cm and a bed volume of 10 mL. Membrane pore size ranged from 50 to 300 μm. According to the manufacturer, the membrane binding capacity for lysozyme was 1 g.

The other cartridge (MemSep® 1010, model CISP 15H 01) was supplied by Millipore Corp. (Bedford, MA). The unit consisted of a stack of 72 SP regenerated cellulose membranes. The stack had a bed height of 1 cm, and a bed volume of 4.9 mL. The membranes had 85% void porosity, and 1.2 μm pore size. The capacity of the cartridge was reported by the manufacturer to be 2.3 meq, and the total binding capacity of lysozyme was 75-125 mg.

The protein recovery cycle consisted of equilibration, loading, washing, and elution. All steps were carried out at a constant flow rate using a Masterflex® drive (model 7520-25, Cole Parmer Instrument Co., Chicago, IL) and a FMI Lab

Pump Jr.® (model RH0CKC, Fluid Metering, Inc., Oyster Bay, NY). Equilibration consisted of pumping 10 bed volumes of the loading/washing buffer (L/W buffer) through the cartridge. Loading was accomplished by pumping whey solution at pH 3.0 through the IEX cartridge to adsorb proteins to the membranes. The L/W buffer was pumped through the unit to used to wash unbound materials from the membrane surface. The cycle was completed by pumping elution buffer (E buffer) through the unit to release bound proteins from the membranes.

When using the Productiv® S cartridge (PSC10), the L/W buffer was 0.1 M citric acid/sodium citrate pH 3.0, the E buffer was 0.2 M ammonium hydroxide/ammonium chloride pH 9.0, and the flow rate was 9.4 mL/min (one bed volume per min). When the MemSep® cartridge (CISP) was used, the L/W buffer was 0.02 M sodium acetate pH 3.0, the E buffer was 0.375 M Tris buffer pH 8.8, and the flow rate was 4.7 mL/min (one bed volume per min). The buffers used with the CISP were vacuum filtered with a 0.2 μm filter (model 66199, Gelman Sciences, Inc., Ann Arbor, MI) prior to use.

Cartridges were cleaned after the elution step. Eight bed volumes of 0.2 M NaOH solution at room temperature were pumped through the cartridge. The cartridge was then submerged in a 60°C water bath. After 1 hr, the cartridge was backflushed with another 8 bed volumes of the NaOH while still in the water bath. The cartridge was then removed from the water bath and backflushed with water at room temperature until the pH of the effluent was less then 8.0. Cleaning was completed by backflushing the cartridge with 16 bed volumes of 0.2 M HCl, followed by water until the pH of the effluent rose above 4. The cartridge was flushed with two bed volumes of L/W buffer prior to storage.

Cycle progress was monitored by a UV detector with a 10-μL-volume, 2-mm-lightpath flow cuvette (model 111, Gilson Medical Electronics, Inc., Middleton, WI) at a wavelength of 280 nm. The detector signal was recorded by a strip-chart recorder and a datalogger (model 50, Electronic Controls Design, Inc., Milwaukie, OR).

Seven separate cycles, each using a different loading volume of whey solution, were performed using the PSC10 to investigate the binding of total nitrogen (TN), non-protein nitrogen (NPN), protein and minerals as a function of the volume of whey solution loaded. In all these experiments, the volume of whey solution was loaded into the PSC10. Then the cartridge was flushed with L/W buffer until the detector signal returned to baseline. The detector signal from one experiment

using a loading volume of 250 mL was digitized and plotted as percent absorbance vs effluent volume. The effluent from the cartridge was collected continuously starting with loading of the whey solution, and ending with flushing with L/W buffer. It was then analyzed for TN, NPN and mineral composition. The elution peak was also collected and analyzed for mineral composition, and absorbance at 280 nm to determine total protein. Loading volumes of 10, 20, 30, 50, 100, 150, and 200 mL were used. One cycle using a loading volume of 50 mL was repeated at a flow rate of 4.7 mL/min. The procedure was repeated using the same PSC10 cartridge and loading volumes of 10, 20, 30, 40, 60, 150, and 250 mL. Four of these loading volumes were duplicates of the first procedure, and three were new. Only elution peaks were collected and analyzed in the later procedure.

Next, the amount of protein and minerals recovered in the elution peak as a function of the volume of whey loaded was determined for the CISP cartridge. Nine separate cycles were performed using loading volumes of 5, 10, 15, 20, 30, 50, 75, 100, and 125 mL of whey solution. This procedure was later duplicated using a different lot number CISP cartridge. The detector signal from the experiment using a loading volume of 75 mL was digitized and plotted as percent absorbance vs effluent volume. In each of these experiments, the elution peak was collected and analyzed for protein and mineral composition.

Protein and Mineral Analyses

The NPN content of raw whey, whey solution, and effluents was determined as follows: proteins were precipitated by adding 5 mL of 48 % (w/w) trichloroacetic acid (TCA) solution to 15 mL of sample. Then the Kjeldahl TN content in the filtrate from TCA precipitation, and in the untreated sample were determined by the University of Wisconsin Soil and Plant Analysis Laboratory. The total protein content of each sample was calculated as 6.38x(TN-NPN). The same laboratory also determined the mineral content of the samples using atomic absorption spectroscopy.

In order to convert the absorbance at 280 nm for each elution peak to total protein concentration, a conversion factor was determined by dialyzing six elution peak samples prior to measurement of total protein content. A 25-mL portion of

each sample was dialyzed against 0.10 M phosphate buffer, pH 8.8, using 2000 molecular weight cut-off dialysis tubing (Spectra/Por® 6, Spectrum, Houston, TX). The TN content of the dialyzed sample was determined, and 1 part dialyzed sample was diluted with 9 parts of 0.375 M Tris buffer pH 8.8 before measurement of the absorbance at 280 nm. Based on the absorbance of each dialyzed and diluted elution peak sample, and the total protein content calculated from the TN content, a conversion factor of 0.7 mg protein/mL/a.u./cm was used to convert the absorbances of the elution peak samples to protein concentration.

RESULTS AND DISCUSSION

Microfiltration

Loading raw whey directly onto the CISP cartridge created a rapid pressure increase, probably due to micron-sized particulates such as lipoproteins [7]. For this reason, the raw whey was microfiltered using a 0.45-μm polysulfone hollow-fiber membrane prior to loading into the cartridges. The turbidity of the permeate from microfiltration was less than that of the raw whey, probably due to a reduction in the lipoprotein content.

Raw whey and whey permeate (the whey solutions) were analyzed for protein, NPN and mineral content to determine if these components were reduced in concentration by microfiltration. The results of the microfiltration of four separate raw whey samples are contained in Table 1. The dilution factor which occurred on adjustment of the pH was used in calculating the original permeate composition. Based on these data, 70% of the total protein in the raw whey was recovered in the microfiltration permeate. This value is only moderately lower than the 79-80% recovery for a metallic microfiltration membrane at 50°C [8]. The permeate contained 84% of the NPN in the raw whey. Microfiltration did not significantly reduce the mineral content of the whey. The 30% reduction in total protein content of the whey due to microfiltration may have resulted from removing relatively more bovine immunoglobulin G and bovine serum albumin than α-lactalbumin and β-lactoglobulin from the raw whey [8].

TABLE 1
Effect of Microfiltration on Whey Composition

	Raw	Permeate
Volume (mL)	1520 ± 30†	750 ± 20
NPN (mg/mL)	0.5 ± 0.2	0.42 ± 0.07
Protein (TN-NPN)x6.38 (mg/mL)	6 ± 1	4.2 ± 0.4
K (mg/mL)	1.3 ± 0.2	1.18 ± 0.05
Na (mg/mL)	0.37 ± 0.02	0.37 ± 0.02
Ca (mg/mL)	0.42 ± 0.09	0.38 ± 0.01
Mg (mg/mL)	0.07 ± 0.01	0.061 ± 0.006

†mean ± st. dev., n = 4

Optimum pH for Protein Adsorption

In the commercial stirred-tank process, using cationic silica-based resins with attached sulfonic groups ($-SO_3^-$), the whey is adjusted to pH 4.5 or lower to maximize protein adsorption [2,9]. For the IEX membrane process, the highest protein adsorption occurred at pH 3.0. A decrease in protein binding was observed when solutions of pH 3.5, 4.0 and 4.5 were used (data not shown). These findings agree well with those for sulfopropyl ion-exchangers which adsorb whey proteins efficiently from pH 1.5 to 3.5, with an optimum pH of 3.0 [4,10].

Composition of the Effluent when Loading Different Volumes of Whey Solution

Table 2 contains the amount of whey components in the loaded whey solution and in the effluent solution from the PSC10 cartridge when loading different volumes. These data were used to determine the degree of binding of each compound to the membrane. For all seven whey loading volumes, the amounts of NPN, potassium, calcium, and magnesium contained in the whey solution loaded into the cartridge nearly equaled the amounts in the effluent solution. Thus, none of these compounds bound to the membrane cartridge.

The amount of sodium loaded into the membrane cartridge came from both the whey solution and the L/W buffer. The amount of sodium loaded into the cartridge nearly equaled the amount in the effluent solution. Thus, sodium was not significantly retained by the membrane cartridge.

Conversely, amounts of TN and total protein in the whey solution loaded into the cartridge were substantially greater than amounts in the effluent solution. As expected, protein strongly bound to the membrane cartridge.

For pure solutions of single proteins, all the protein loaded into an IEX membrane binds until the saturation capacity is reached, at which point no more protein is retained [6]. As a result, prior to saturation, the total amount of protein bound to the cartridge should increase linearly with increasing loading volume.

In Fig. 1, however, the total amount of protein bound to the cartridge P (mg) generally increased non-linearly with increasing loading volume V (mL). The protein binding data (solid triangles) were fit by least-squares regression to the equation:

TABLE 2

Contents of Effluent vs Loading Volume of Whey Solution Using a PSC10 Cartridge

Loading volume (mL)	Effluent volume (mL)	TN (mg)		NPN (mg)		Protein (TN-NPN)x6.38 (mg)		K (mg)		Ca (mg)		Mg (mg)		Na (mg)	
		L†	E	L	E	L	E	L	E	L	E	L	E	L	E
10	73	10	1	3	3	42	-15	10	13	3	3	1	1	79	73
20	58	19	5	6	5	83	4	21	24	7	6	1	1	52	52
30	101	29	7	10	2	125	32	31	36	10	10	2	2	95	82
50	107	49	23	16	19	208	24	51	59	17	16	3	3	84	76
100	162	97	45	32	34	416	72	103	97	34	30	6	5	106	120
150	210	146	95	48	49	624	293	154	170	52	47	9	9	121	123
200	260	194	131	64	74	831	361	206	214	69	71	12	12	137	135
50*	81	49	19	16	17	208	15	51	58	17	18	3	3	53	58

†L = mg loaded into the membrane cartridge, E = mg in effluent solution

*flow rate = 4.7 mL/min

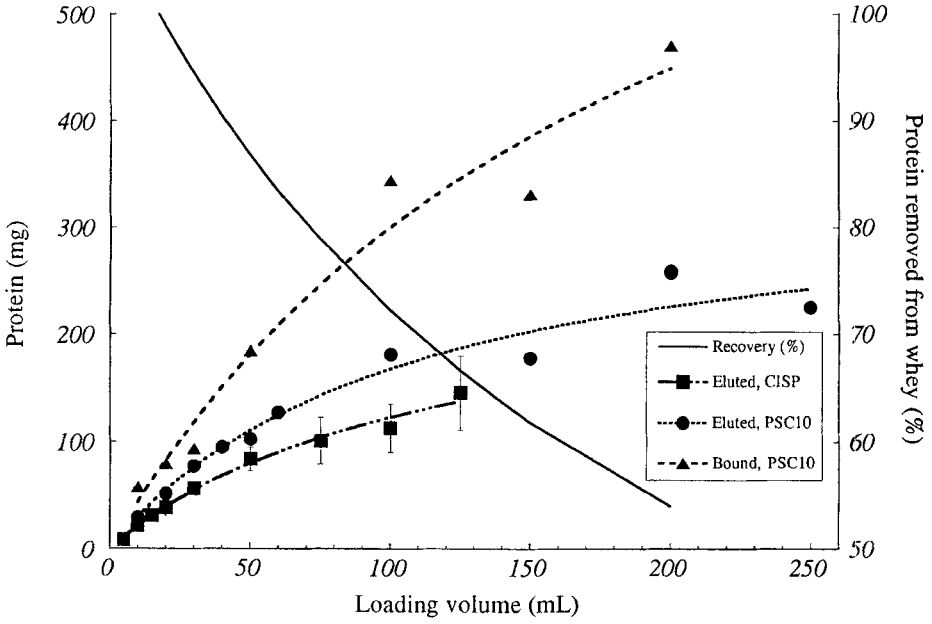

FIGURE 1. Protein bound to the PSC10, and protein in the elution peaks for the PSC10 and CISP vs the volume of whey solution loaded. Also plotted is the percentage of whey protein loaded which bound to the PSC10. Error bars indicate ± st. dev., n = 2.

$$P = p\frac{(V)}{(V+v)}$$

resulting in p = 890 mg, and v = 197 mL. The parameter p is the maximum amount of protein that would bind to the cartridge at infinite loading volume. The parameter v is the loading volume for binding of 50% of p.

The non-linear behavior of protein bound vs. volume loaded may have resulted from competitive adsorption for membrane binding sites between the individual proteins in whey. Competitive adsorption occurs for adsorption of whey proteins to cation-exchange membranes [6], and for whey protein adsorption to columns packed with Spherosil S cation-exchange beads [10].

Using the non-linear fit from Eq. (1), the greatest amount of protein which bound to the membrane was 450 mg for a loading volume of 200 mL. However,

as the loading volume increased, a smaller percentage of the protein in the whey solution loaded bound to the membrane cartridge. Using Eq. (1), the percent protein recovery was calculated and plotted in Fig. 1. Protein recovery was 87% or more for loading volumes of 50 mL or less, but it decreased to 54% for the highest loading volume of 200 mL. Therefore, there was a balance between operating conditions at one extreme where the percent retention is highest, and the other extreme where the amount of protein bound to the membrane was highest.

Composition of the Elution Peaks when Loading Different Volumes of Whey Solution

In these experiments, the amounts of protein and minerals in the elution peaks were determined after loading 10 to 250 mL of whey solution into the PSC10 cartridge, and 5 to 125 mL of whey solution into the CISP cartridge. This range of loading volumes for the PSC10 and the CISP was from 1 to 25 bed volumes. These loading volumes contained from less than 5% to over 100% of the amount of protein able to bind to the cartridges as reported by the manufacturers.

Tables 3 and 4 contain the protein concentration and the amount of minerals in the elution peaks for the PSC10 and CISP cartridges, respectively. The amounts of potassium, calcium, and magnesium in the elution peaks were negligible. These results agree with the results of Table 2, where these minerals were found not to bind to the cartridge. The amounts of sodium in the elution peaks were relatively small and constant, but not negligible. The average amount of sodium in the elution peaks was 25 mg for the PSC10, and 8 mg for the CISP. As mentioned before, sodium was not retained by the PSC10 cartridge (Table 2). However, before loading, the membrane cartridge was probably in the sodium form due to the equilibration step with L/W buffer. The sodium in the elution peak may have resulted from displacement of this sodium by the elution buffer.

The total amount of protein in the elution peak generally increased with increasing loading volume for both the PSC10 and CISP (Fig. 1). The data were fit to Eq. (1) resulting in p = 345 mg, and v = 106 mL for the PSC10 (solid circles), and p = 265 mg, and v = 117 mL for the CISP (solid squares). Using Eq. (1), the greatest amount of protein eluted from the PSC10 was 240 mg for a loading volume of 250 mL (25 bed volumes). For the CISP, 140 mg was eluted

TABLE 3
Contents of Elution Peak vs Loading Volume of Whey Solution Using a PSC10 Cartridge

Loading volume (mL)	Eluant volume (mL)	Protein (mg/mL)	K (mg)	Ca (mg)	Mg (mg)	Na (mg)
10	64 ± 4†	0.46 ± 0.02	0.05 ± 0.06	0.5 ± 0.2	0.1 ± 0.0	29 ± 7
20	54 ± 0	0.95 ± 0.01	0.13 ± 0.04	0.8 ± 0.2	0.15 ± 0.07	27 ± 5
30	77 ± 6	1.00 ± 0.02	0.15 ± 0.06	0.6 ± 0.0	0.1 ± 0.0	24 ± 1
40	79	1.20	0.1	0.3	0.7	23
50	67	1.53	0.2	0.9	0.2	21
60	67	1.90	0.2	0.7	0.1	26
100	94	1.92	0.1	0.3	0.1	26
150	93 ± 4	1.91 ± 0.07	0.4 ± 0.5	0.3 ± 0.3	0.1 ± 0.0	27 ± 4
200	125	2.07	0.4	0.5	0.1	25
250	88	2.56	0.2	0.4	0.1	21
50*	75	1.78	0.2	1.0	0.2	30

†mean ± st. dev., n=2

*flow rate = 4.7 mL/min

TABLE 4
Contents of Elution Peak vs Loading Volume of Whey Solution Using a CISP Cartridge

Loading volume (mL)	Eluant volume (mL)	Protein (mg/mL)	K (mg)	Ca (mg)	Mg (mg)	Na (mg)
5	14 ± 4†	0.6 ± 0.1	0.6 ± 0.7	0.01 ± 0.01	0.006 ± 0.006	8 ± 4
10	35 ± 4	0.6 ± 0.2	4 ± 6	1 ± 1	0.2 ± 0.3	8.60 ± 0.02
15	30 ± 3	1.0 ± 0.1	4 ± 5	1 ± 1	0.2 ± 0.3	7.28 ± 0.08
20	39 ± 5	1.0 ± 0.3	2 ± 2	2 ± 2	0.3 ± 0.2	7.16 ± 0.02
30	42 ± 4	1.4 ± 0.1	1 ± 1	2 ± 2	0.25 ± 0.07	8 ± 1
50	54.3 ± 0.4	1.5 ± 0.2	2 ± 2	2 ± 1	0.34 ± 0.08	7.6 ± 0.4
75	73 ± 9	1.4 ± 0.1	1.0 ± 0.7	2 ± 1	0.27 ± 0.03	9.5 ± 0.8
100	81 ± 2	1.4 ± 0.3	0.8 ± 0.4	3 ± 1	0.38 ± 0.05	8.0 ± 0.9
125	116 ± 7	1.3 ± 0.4	1.3 ± 0.9	2.8 ± 0.4	0.4 ± 0.1	9 ± 1

†mean ± st. dev., n=2

for a loading volume of 125 mL (25 bed volumes). However, the membrane volume of the PSC10 was about twice that of the CISP. The cartridges had similar capacities when compared on a basis of mg protein per mL membrane. The greatest amount of protein eluted from the CISP was 29 mg per mL of membrane, and from the PSC10 was 24 mg per mL of membrane.

Increasing the volume of whey solution loaded decreased the ratio of minerals-to-protein in the elution peak. The mineral-to-protein ratios of the elution peaks were as low as 0.1 mg/mg for the PSC10 using a 250 mL loading volume (Table 3), and 0.09 mg/mg for the CISP and a 125 mL loading volume (Table 4). In contrast, microfiltered whey permeate contained 0.47 mg minerals per mg protein (Table 1). Therefore, IEX membranes may be used to produce whey protein with a low mineral content. This is preferred in the production of infant formula and dietetic food products, because high mineral content can affect both the flavor and nutritional value of these products [9,11].

Breakthrough Curves from the PSC10 and CISP

Not all the protein which bound to the PSC10 was desorbed into the elution peak. Based on the fits of Eq. (1) to the data in Fig. 1, and Tables 2 and 3, 69% of the protein retained by the PSC10 was desorbed into the elution peak for a loading volume of 10 mL. This value dropped to 50% for a loading volume of 200 mL. Much of the protein which did not desorb into the elution peak can be accounted for by examining the digitized breakthrough curves.

In a typical breakthrough curve for the PSC10 (Fig. 2), the effluent absorbance rose rapidly to the feed solution absorbance, and slowly returned to baseline during washing. The elution peak emerged over an effluent volume of 142 mL. Only the first 88 mL of the elution peak were collected in order to avoid dilution of the peak due to tailing. Thus, a small amount of the protein desorbed from the membrane was lost in the 54 mL of the elution peak which was not collected. Finally, the small peak that emerged during cleaning with 0.2 M NaOH contained protein which was not desorbed by the elution buffer. The sum of these losses may account for the difference in the amount of protein collected in the elution peak (Table 3) compared to the amount bound to the cartridge after loading and washing (Table 2).

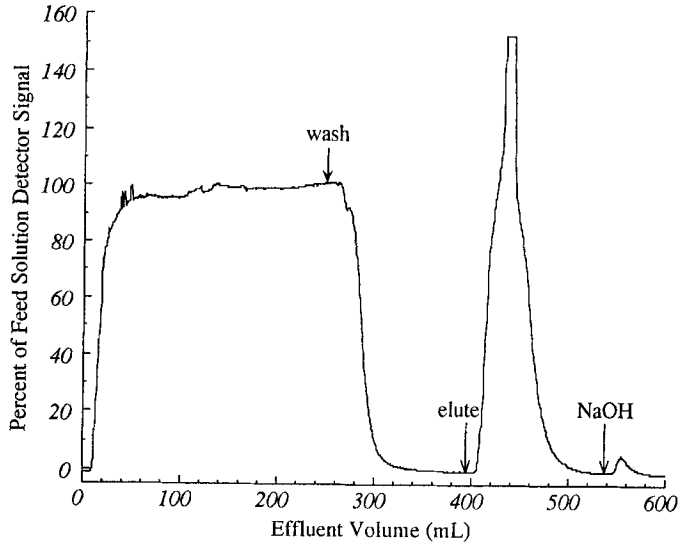

FIGURE 2. Breakthrough curve from the UV detector for the PSC10 cartridge. An aliquot of 250 mL whey solution pH 3 was loaded into the cartridge. The cartridge was washed using 145 mL 0.1 M citric acid/sodium citrate pH 3, and eluted using 142 mL 0.2 M ammonium hydroxide/ammonium chloride pH 9. The flow rate was 9.4 mL/min.

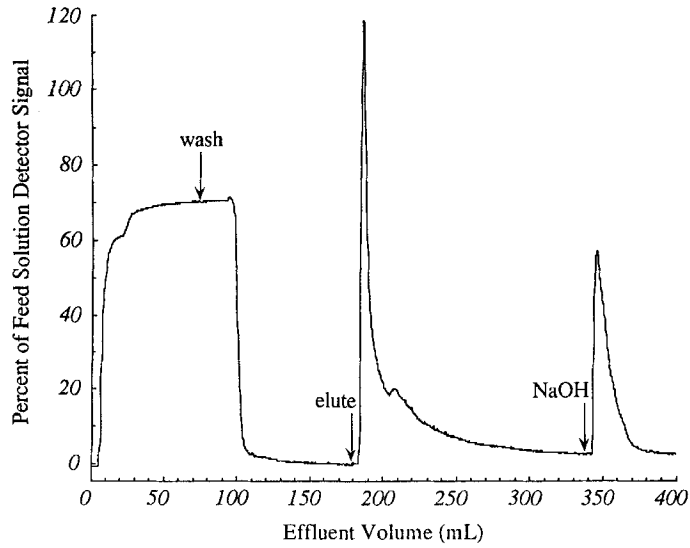

FIGURE 3. Breakthrough curve from the UV detector for the CISP cartridge. An aliquot of 75 mL whey solution pH 3 was loaded into the cartridge. The cartridge was washed using 103 mL 0.02 M sodium acetate pH 3, and eluted using 154 mL 0.375 M Tris pH 8.8. The flow rate was 4.7 mL/min.

In the breakthrough curve for the CISP (Fig. 3), the effluent absorbance reached a plateau at 70% of the feed solution absorbance, and slowly returned to baseline during washing. The elution peak emerged over an effluent volume of 154 mL. Because the elution peak had a long tail, only approximately the first 73 mL were collected. Thus, a significant amount of the desorbed protein was lost in the 81 mL of the elution peak which was not collected. Finally, the peak that emerged during cleaning with 0.2 M NaOH contained a large amount of protein which was not desorbed by the elution buffer. Based on the breakthrough curves in Figs. 2 and 3, the sum of the losses of protein for the CISP appears to be greater than those for the PSC10.

The failure of the effluent absorbance from the CISP to reach the feed solution absorbance in Fig. 3 could have resulted from removal of trace amounts of sub-micron particulates from the feed solution. The effluent from the CISP was visibly less turbid than the feed solution. The effluent absorbance from the PSC10 did reach the feed solution absorbance in Fig. 2. The larger pore size of the PSC10 (50 to 300 μm) compared to the CISP (1.2 μm) probably resulted in negligible removal of sub-micron particulates from the feed solution by the PSC10.

Effect of Flow Rate on Protein Recovery from the PSC10

In order to determine if the results depended on flow rate, the cycle using a loading volume of 50 mL was repeated at 4.7 mL/min, one half the standard value. From Table 2, none of the NPN or minerals bound to the membrane cartridge, in agreement with the results from the cycle using the standard flow rate. Protein binding was 5% higher compared to the cycle using the standard flow rate. However, this difference was within the normal range of variation of the results and may not have been significant. From Table 3, the amounts of minerals in the elution peak were nearly identical to those for the higher flow rate, in agreement with all previous results on mineral retention. The amount of protein in the elution peak for the lower flow rate was 30% higher than for the cycle using the standard flow rate. However, this increase in amount of protein may have resulted partly from the larger volume of the elution peak collected at the lower flow rate (Table 3). Three conclusions can be made: (1) NPN and mineral binding did not depend on flow rate, (2) the NPN and mineral binding data were highly reproducible, (3) protein binding did not depend strongly on flow rate.

Economic Considerations

An economic analysis of the two membrane cartridges favors the PSC10. The selling price of the PSC10 is 1.2 % of the selling price of the CISP for laboratory-scale cartridges on a per mL of membrane basis. However, the protein binding capacities of the cartridges are similar on a per mL of membrane basis.

Microfiltration of the whey substantially adds to the overall processing costs because it reduces the protein content of the whey by 30%, and it involves an extra processing step. Microfiltration was required for the CISP because direct loading of whey created a rapid increase in pressure. The larger pore size of the PSC10 (50 to 300 μm) compared to the CISP (1.2 μm) may allow for direct loading of whey without microfiltration, and it reduces the pressure drop at a given flow rate. The pressure drop was 10 psi at 9.4 mL/min for the PSC10, and 30 psi at 4.9 mL/min for the CISP. Consequently, whey processing costs for the PSC10 may be lower than for the CISP.

Because of low pressure drops at high flow rates, the cycling times for IEX membranes would be much shorter than those for commercial stirred-tank processes, and for packed-column processes, which have cycling times well over an hour [10]. Shorter cycling times result in more efficient utilization of the IEX groups on the membrane, which reduces the IEX capacity needed to achieve a fixed protein output compared to stirred-tank processes. Reduced capacity demands should translate into reduced capital costs for a new plant, especially if IEX membranes can be retrofitted into existing ultrafiltration membrane equipment. Based on these results, IEX membranes are a promising new method for whey protein isolation.

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