

Glucagon and Insulin Binding to Liver Membranes in a Partially Nephrectomized Uremic Rat Model

VIJAY SOMAN and PHILIP FELIG

From the Department of Internal Medicine, Yale University School of Medicine, New Haven, Connecticut 06510

ABSTRACT To investigate the role of glucagon and insulin receptor binding in the glucagon hypersensitivity and insulin resistance which characterize the glucose intolerance of uremia, liver plasma membranes were prepared from control rats (blood urea nitrogen [BUN] 15 ± 1 mg/100 ml, creatinine 0.7 ± 0.2 mg/100 ml), and from 70% nephrectomized rats (BUN 30 ± 2 mg/100 ml, creatinine 2.2 ± 0.2 mg/100 ml), and from 90% nephrectomized rats (BUN 46 ± 3 mg/100 ml, creatinine 4.20 ± 0.7 mg/100 ml), 4 wk after surgery. As compared to controls, the 90% nephrectomized rats had significantly higher levels of plasma glucose (95 ± 4 vs. 125 ± 11 mg/100 ml), plasma insulin (28 ± 9 vs. 52 ± 11 μ U/ml), and plasma glucagon (28 ± 5 vs. 215 ± 18 pg/ml). Similar, but less marked, elevations were observed in the 70% nephrectomized animals.

In liver plasma membranes from nephrectomized rats, specific binding of 125 I-glucagon was increased by 80–120%. Furthermore, glucagon (2μ M)-stimulated adenylate cyclase activity in nephrectomized rats was twofold higher than in controls. In contrast, fluoride-stimulated adenylate cyclase activity was similar in both groups of rats. In marked contrast to glucagon binding, specific binding of 125 I-insulin to liver membranes from nephrectomized rats was reduced by 40–50% as compared to controls. Data analysis suggested that the changes in both glucagon and insulin binding are a consequence of alterations in binding capacity rather than changes in affinity. Liver plasma membranes from nephrectomized rats degraded 125 I-glucagon and 125 I-insulin to the same extent as control rats.

These results demonstrate that: (a) the 70 and 90% nephrectomized rats simulate the hyperglycemia, hyperinsulinemia, and hyperglucagonemia observed in clinical uremia; (b) in these animals specific binding of glucagon to liver membranes is increased and is accompanied by higher glucagon-stimulated

adenylate cyclase activity; and (c) specific binding of insulin is markedly decreased. These findings thus provide evidence of oppositely directed, simultaneous changes in glucagon and insulin receptor binding in partially nephrectomized rats. Such changes may account for the hypersensitivity to glucagon and may contribute to resistance to insulin observed in the glucose intolerance of uremia.

INTRODUCTION

Chronic renal failure is commonly associated with glucose intolerance (1). The reduction in glucose tolerance is characterized by increased insulin levels (2) and diminished responses to endogenous (3) and exogenous insulin (4), suggesting insulin resistance. In addition to alterations in insulin, uremia is characterized by hyperglucagonemia (5, 6) and an increased sensitivity to glucagon-induced hyperglycemia (6). This hypersensitivity to glucagon is reversible after dialysis (6). The pathogenesis and cellular mechanism of glucagon hypersensitivity and insulin resistance in uremia have not been established. Changes in insulin binding to tissue receptors have recently been implicated in the insulin resistance of obesity (7) and in diabetic patients with acanthosis nigricans (8). Only limited data are available concerning altered glucagon binding in disorders of carbohydrate metabolism (9, 10). The present study was consequently undertaken to determine whether increased glucagon sensitivity and insulin resistance in uremia might be mediated by alterations in the binding of these peptide hormones to their specific liver plasma membrane receptors. In this investigation, insulin and glucagon binding to hepatic plasma membranes has been studied in a uremic rat model (11).

METHODS

Experimental animals. Adult Sprague-Dawley rats weighing 200–300 g were used in all experiments. Three

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groups of rats were studied: control rats with intact kidneys, and two groups of experimental animals with renal insufficiency. The renal insufficiency was produced by surgical ablation of approximately 70% (group I) and 90% (group II) of the renal mass using the technique described by Kaufman et al. (11). All animals were placed in individual cages and allowed 20 g of standard Purina chow per day (Ralston Purina Co., St. Louis, Mo.). All food was consumed daily, indicating that dietary intake was comparable in all three groups. The body weights (mean \pm SEM) of the three groups of experimental animals at the beginning and at the end of the 4-wk study period were as follows: control rats, 202 \pm 12 and 322 \pm 14 g, respectively; 70% nephrectomy group, 196 \pm 10 and 306 \pm 19 g, respectively; and 90% nephrectomy group, 206 \pm 15 and 291 \pm 12 g, respectively. Animals were fasted 8–10 h before sacrifice. They were sacrificed 28 days after surgery, since previous work has shown that the compensatory response to renal ablation is complete by 14–21 days after surgery (12). Livers were quickly removed from 10 to 15 rats from each group (control, 70% nephrectomy, and 90% nephrectomy), and blood was obtained by aortic puncture for measurement of blood urea nitrogen (BUN), creatinine, glucose, insulin, and glucagon.

Preparation of liver plasma membranes. After removal, livers were quickly minced in 0.25 M ice-cold sucrose and homogenized in 0.001 M NaHCO₃ solution in a Dounce homogenizer at 4°C (Kontes Co., Vineland, N. J.). Partially purified plasma membranes were prepared by the method of Neville (13) as modified by Pohl et al. (14). The preparation sequence was rigidly followed for membranes of all three groups of rats, and specific activity of the membrane marker enzyme, 5'-nucleotidase was measured by the method of Avruch and Wallach (15). Membrane protein was estimated by the method of Lowry et al. (16). Membrane preparations were stored in small aliquots at -70°C for 3 mo without any significant decrease in adenylate cyclase activity or hormone binding.

Iodination of insulin and glucagon. ¹²⁵I-Insulin was prepared by the chloramine-T method at specific activities of 100–150 μ Ci/ μ g according to the method of Freychet et al. (17). This method has been shown to yield a biologically active moniodoinsulin preparation.

Glucagon was iodinated by a modification (18) of the Hunter and Greenwood method (19). 10 μ l of a 10⁻⁴ M glucagon solution (1 nmol) in 0.5 M NaPO₄ buffer, pH 7.4 was added to 1 nmol of carrier-free ¹²⁵I-Na (in 0.1 N NaOH) in a 13 \times 100-mm glass tube. A freshly prepared solution of chloramine-T (10 μ l of 3.5 mg/ml in 0.5 M phosphate buffer) was added, and the reagents were mixed rapidly. 50 μ l of sodium metabisulphite solution (2 mg/ml) was added immediately (within 5 s) and mixed rapidly. This was immediately followed by addition of 150 μ l of 10 mM NaPO₄ buffer, pH 7.4 with 1% bovine serum albumin (BSA).¹ The reaction mixture was applied to a 0.4-ml column of cellulose in a Pasteur pipette which had been equilibrated with phosphate buffer (10 mM pH 7.4%) and was washed with 1% BSA solution. The column was eluted successively with 10 mM phosphate buffer, containing 1% BSA, H₂O, and 50% ethanol in 10 mM Tris HCl, pH 7.6 (17). The specific activity of ¹²⁵I-glucagon was 150–200 μ Ci/ μ g. Trichloroacetic acid precipitability of both iodinated hormones was ~95%. Iodinated hormones were stored at -20°C and used within 2 wk.

Glucagon binding assay. The binding of ¹²⁵I-glucagon to hepatic plasma membranes were carried out according to

the method of Rodbell et al. (20). Liver membranes (30–50 μ g protein) were incubated for 15 min at 30°C in a medium containing 20 mM Tris-HCl, 1 mM EDTA, 2% BSA pH 7.6, 2 nM ¹²⁵I-glucagon and varying concentrations of unlabeled glucagon. The incubation volume was 250 μ l. At the end of the incubation period, 50- μ l aliquots of the incubation mixture were layered over 250 μ l of a solution containing 20 mM Tris-HCl, pH 7.6, with 2% BSA in plastic microfuge tubes. The tubes were centrifuged immediately in a Beckman microfuge model B (Beckman Instruments, Inc., Fullerton, Calif.) at 4°C for 5 min. The supernatant fluid was aspirated, and the pellet was gently washed with 300 μ l of cold 10% sucrose. After aspirating the fluid, the tip of the centrifuge tube was cut just above the pellet, and the pellet was counted in a gamma counter. The specific binding of ¹²⁵I-glucagon was calculated by subtracting non-specific binding ¹²⁵I-glucagon bound in the presence of 1,000 ng/ml glucagon from the total ¹²⁵I-glucagon binding (in the absence of unlabeled glucagon).

Measurements of adenylate cyclase activity. Adenylate cyclase activity in liver membranes was measured according to the procedure described by Steiner et al. (21). The incubation medium contained in 100 μ l, 20 mM Tris-HCl, pH 7.6, 5 mM MgCl₂, 1 mM EDTA, 10 mM theophylline, 0.15% BSA, 4 mM ATP, creatine kinase (1 mg/ml), 25 mM phosphocreatine, and 50–60 μ g of membrane protein. Creatine kinase and phosphocreatine solutions were prepared fresh for each experiment. Stimulation of adenylate cyclase activity was measured by the addition 2 μ M glucagon and 15 mM NaF. Incubation was carried out for 10 min at 30°C, and the reaction was stopped by boiling for 3 min. After centrifugation at 3,000 rpm for 15 min at 5°C, aliquots of supernate were assayed for 3',5'-cyclic AMP by radioimmunoassay (21). Specificity of the assay was confirmed by demonstrating that cyclic AMP could no longer be measured after treatment of membranes with purified bovine phosphodiesterase. Recovery of added cyclic AMP in the assay system was at least 90%.

Insulin binding assay. ¹²⁵I-Insulin binding studies were conducted at 30°C in Krebs-Ringer phosphate buffer (140 mM NaCl, 1.7 mM KCl, 0.4 mM Mg SO₄, 1.5 mM KH₂ PO₄) pH 7.5, containing 1% BSA in a final volume of 0.5 ml/incubation tube. The latter contained 0.2 ng/ml of ¹²⁵I-insulin, 80–120 μ g of membrane protein, and varying concentrations of unlabeled insulin. At the end of the 60-min incubation period, 200- μ l aliquots were layered over 100 μ l of Krebs-Ringer phosphate buffer in microfuge tubes, and ¹²⁵I-insulin bound to membranes was separated by the method used for glucagon binding described earlier.

Data analysis of insulin binding. The specific binding of ¹²⁵I-insulin was calculated by subtracting nonspecific binding (¹²⁵I-insulin bound in the presence of 1,000 ng/ml of unlabeled insulin) from the total ¹²⁵I-insulin binding (¹²⁵I-insulin bound in absence of unlabeled insulin). Insulin binding data were analyzed by two methods, Scatchard analysis (22) and the "average affinity profile" (23). In Scatchard analysis (22), bound/free ¹²⁵I-insulin is plotted as a function of bound (*B*) hormone, and the total binding capacity or total receptor concentration (*R*₀) is derived from the point where the linear extrapolation of the curve intersects the horizontal axis. Because the insulin receptor sites are not independent of one another (24), estimation of affinities of the binding sites for curvilinear Scatchard plots may not be valid (25). Therefore, we have also analyzed insulin binding data employing the "average affinity profile" method described by De Meyts and Roth (23). The average affinity profile expresses the relationship between average affinity for insulin (\bar{K}) and receptor occupancy (\bar{Y}), and the validity

¹Abbreviation used in this paper: BSA, bovine serum albumin.

of this analysis does not depend upon assigning a particular model to the molecular mechanisms involved in the cooperativity behavior of insulin-binding sites (23). At any point on the Scatchard curve, the average affinity = $K_i = [(B/F)_i] / (R_o - B_i)$ where B_i is the concentration of bound hormone and $(B/F)_i$ = bound/free hormone at that point. In his method affinity (K) is plotted as a function of fractional occupancy of the receptor ($Y = B/R_o$), and the plot displays the average affinity of the receptor at all levels of receptor occupancy (23).

Glucagon and insulin degradation by liver plasma membranes. Liver plasma membranes from eight control and eight uremic rats (90% nephrectomy) were incubated at a concentration of 0.2 mg membrane protein/ml with labeled glucagon and insulin under the respective binding conditions described earlier. At the end of the incubation period, the incubation mixture was transferred to a microfuge tube and centrifuged for 2 min at 10,000 g in a Beckman microfuge model B. The supernate was divided into aliquots, and the degradation of the labeled hormones in the supernate was measured by the following methods. (a) *Precipitation by trichloroacetic acid (TCA).* 50- μ l aliquots of the supernates were transferred to tubes containing 1 ml of chilled 0.025 M Veronal (Winthrop Laboratories, Sterling Drug Co., New York) buffer, pH 8.6 with 0.25% BSA. 1 ml of 10% TCA was immediately added, and the tubes were centrifuged for 10 min at 2,500 rpm. Radioactivity was then counted in each precipitate and supernate. Reactivity precipitable by TCA indicates undamaged hormone. (b) *Binding to liver membranes.* 100- μ l aliquots of the supernates were incubated with fresh liver membranes (0.2 mg/ml) under glucagon and insulin binding conditions, and specific binding of labeled hormones was calculated as described earlier. (c) *Adenylate cyclase activation.* 50- μ l aliquot of supernate from 125 I-glucagon-binding experiment was assayed for adenylate cyclase activity by the method described earlier.

Expression of results: in each experiment, appropriate control tubes were prepared which were identical to experimental tubes in all respects except that liver membranes were omitted. In all experiments, there was less than 5% degradation of labeled hormones in control tubes. Percentage of intact hormone (in methods b and c, above) was calculated by using standard curves for glucagon and insulin binding and for adenylate cyclase activity. Results were calculated as follows: % degradation of labeled hormone by liver membrane = $1 - (\% \text{ Intact hormone in experimental tube}) / (\% \text{ Intact hormone in control tube}) \times 100$.

Reagents. Crystalline porcine glucagon and crystalline porcine insulin were a gift from Eli Lilly and Co., Indianapolis, Ind. Carrier-free 125 I-Na was obtained from New England Nuclear, Boston, Mass. Cellulose powder was obtained from Arthur H. Thomas Co., Philadelphia, Pa. Reagents for cyclic AMP radioimmunoassay were purchased from Schwarz/Mann Div., Becton-Dickinson & Co., Orangeburg, N. Y. All other reagents were analytical grade.

Blood and plasma measurements. Plasma immunoreactive insulin and immunoreactive glucagon (using Unger antibody 30K) were determined as described previously (26). Glucose was measured by the glucose oxidase technique (27). BUN and creatinine were determined by standard laboratory technics.

RESULTS

As shown in Table I, the BUN was double the control value in the 70% nephrectomized rats and three times the control level in the 90% nephrectomy group.

Creatinine levels were similarly elevated in nephrectomized animals. Plasma glucose concentrations were 25–30 mg/100 ml higher in both groups of uremic rats. Plasma insulin was 50 and 95% higher in 70 and 90% nephrectomized rats respectively, as compared to normals. In addition, plasma glucagon levels were increased fourfold in the 70% nephrectomized group and rose sixfold in the 90% nephrectomized rats.

Evaluation of membrane purification procedure. Table II summarizes the protein yield and 5'-nucleotidase activity in whole liver homogenates and partially purified membranes from control and 90% nephrectomized rats. It is evident that the yield of protein and the activity of 5'-nucleotidase were virtually identical in both groups of rats. These findings provide evidence that nephrectomy and azotemia had no systematic effect on the membrane isolation procedure to account for the differences in hormone binding and enzyme activity described below.

Effect of nephrectomy on glucagon binding and adenylate cyclase activity. Specific binding of 125 I-glucagon was studied in the control rats and in the two groups of nephrectomized rats. Glucagon binding was found to be linear over a range of protein concentrations of 0.025–1.2 mg/ml. The results shown in Table III are calculated for 0.2 mg membrane protein/ml. Specific binding of 125 I-glucagon was 80 and 120% higher in the 70 and 90% nephrectomized rats respectively, than in control rats ($P < 0.001$, Table III). In contrast to specific binding of 125 I-glucagon, the non-specific binding of labeled glucagon was identical in control (1.3%) and in 70 and 90% nephrectomized rats (1.4 and 1.5%, Table III).

The finding of significantly increased specific binding of glucagon in uremic rats led us to investi-

TABLE I
Influence of Nephrectomy on BUN and Plasma Creatinine, Glucose, Insulin, and Glucagon*

	Control rats (n = 15)	Uremic rats	
		Group I, 70% nephrectomy (n = 9)	Group II, 90% nephrectomy (n = 15)
BUN, mg/100 ml	15 \pm 1	30 \pm 2	46 \pm 3
Creatinine, mg/100 ml	0.67 \pm 0.16	2.20 \pm 0.22	4.21 \pm 0.73
Glucose, mg/100 ml	95 \pm 4	120 \pm 7	125 \pm 9
Insulin, μ U/ml	28 \pm 9	45 \pm 8	52 \pm 11
Glucagon, pg/ml	38 \pm 5	149 \pm 15	215 \pm 18

* Data are presented as the mean \pm SE.

TABLE II
Protein Yield and 5'-Nucleotidase Activity in Liver Plasma Membranes Prepared from Control and 90% Nephrectomized Rats

	Total protein*		5'-Nucleotidase activity†	
	Control rats	Uremic rats (90% nephrectomy)	Control rats	Uremic rats (90% nephrectomy)
	<i>mg/10 g of liver wet wt</i>		<i>μmol of 5'-AMP hydrolyzed/mg protein/h</i>	
Whole liver homogenate	1,350±98	1,296±108	0.65±0.05	0.62±0.10
Partially purified membranes	7.0±0.1	6.7±0.1	6.92±0.15	6.33±0.11
Purification of marker enzyme	—	—	10.6	10.2

* Mean±SE of 15 experiments from each group.

† Mean±SE of nine experiments from each group.

gate the adenylate cyclase activity in liver plasma membranes from these rats, since activation of adenylate cyclase is the next well-recognized step in the interaction between glucagon and its target organs. Both basal and stimulated adenylate cyclase activity was measured in liver membranes from each group of rats. The data are summarized in Table IV. In both groups of uremic rats basal adenylate cyclase activity was 50% higher than in control rats ($P < 0.01$). Furthermore, glucagon-stimulated adenylate cyclase activity in uremic rats was 90–100% higher than in control rats ($P < 0.001$, Table IV). The absolute increment above basal in adenylate cyclase activity induced by glucagon was 3.22 ± 0.15 in control rats as compared to 6.28 ± 0.25 in 70% nephrectomized rats ($P < 0.001$) and 6.59 ± 0.30 in 90% nephrectomized rats ($P < 0.001$). In both control and uremic rats, when 15 mM of NaF was added, adenylate cyclase activity was stimulated to a lesser extent than by addition of 2 μM of glucagon (Table IV). In contrast to the effects of glucagon, the increment induced by NaF in controls (2.56 ± 0.30) was not significantly different from uremics (2.80 ± 0.30 and 2.82 ± 0.25 , $P > 0.1$). Stimulated adenylate cyclase activity was also studied by the addition of maximal concentrations of both glucagon and NaF to the same incubation tubes. The results indicate

that fluoride and glucagon together failed to stimulate the enzyme more than glucagon alone (Table IV).

In Fig. 1, the effects of varying concentrations of glucagon on the binding of ^{125}I -glucagon and on glucagon-stimulated adenylate cyclase activity are compared. In uremic rats ^{125}I -glucagon binding was higher than in control rats at each glucagon concentration. Based on the specific activity of the labeled glucagon the amount of glucagon bound at saturation was calculated to be 3.8 pmol/mg protein in control rats and 7.8 pmol/mg protein in 90% nephrectomized rats. The range of concentrations over which labeled glucagon showed an increase in binding to liver membranes was virtually the same as that found for activation of adenylate cyclase by native glucagon. This was true in both control and nephrectomized rats. The concentration of glucagon giving half-maximal binding or activation of adenylate cyclase was approximately 5 nM in both control and 90% nephrectomized rats. In both groups of rats, saturation of binding sites or activation of adenylate cyclase occurred in the range of 100–250 nM of glucagon.

Degradation of glucagon by liver membranes. To examine the possibility that decreased glucagon degradation by liver membranes from uremic rats may account for increased glucagon binding by these mem-

TABLE III
*Influence of Nephrectomy on Glucagon Binding to Liver Membranes**

Experimental group	^{125}I -Glucagon bound		Specific binding of ^{125}I -glucagon
	Without unlabeled glucagon	With 1,000 ng/ml unlabeled glucagon	
	<i>cpm</i>		<i>%</i>
Control rats ($n = 15$)	30,375±1,525	3,375±475	10.8±0.4
70% Nephrectomized rats ($n = 9$)	50,155±2,015	3,645±495	18.6±0.6
90% Nephrectomized rats ($n = 15$)	59,110±2,895	3,750±580	22.1±0.9

* Data are presented as mean±SE for 0.2 mg membrane protein/ml of incubation medium. Total ^{125}I -glucagon added per tube was ~250,000 cpm.

TABLE IV
Influence of Nephrectomy on Adenylate Cyclase Activity
in Liver Plasma Membranes*

	Adenylate cyclase activity		
	Control rats (n = 15)	Uremic rats	
		70% nephrectomy (n = 9)	90% nephrectomy (n = 15)
	nmol 3',5'-cyclic AMP/mg protein/10 min		
Basal	0.40±0.05	0.56±0.08	0.61±0.05
Glucagon, 2 μM	3.62±0.15	6.84±0.25	7.20±0.30
NaF, 15 mM	2.96±0.32	3.36±0.30	3.43±0.23
Glucagon, 2 μM + NaF, 15 mM	3.65±0.20	6.76±0.22	7.31±0.35

* Data are presented as the mean±SE.

branes, the glucagon inactivation process was studied. Table V shows the degradation of ¹²⁵I-glucagon by liver membranes from control and nephrectomized rats. Glucagon degradation activity was found to be linear over a membrane protein concentration of 0.05–2.5 mg/ml of incubation medium. Liver membranes from control and uremic rats inactivated glucagon to the same extent (40–45%) at a membrane protein concentration of 0.2 mg/ml.

Effect of nephrectomy on insulin binding in liver membranes. To examine the possibility that insulin resistance observed in uremic rats may be related to alterations in insulin binding, we studied the binding of monoiodoinsulin to liver plasma membranes from 15 control rats and 15 uremic rats (90% nephrectomy). As shown in Table VI the specific binding of ¹²⁵I-insulin in uremic rats was 45% lower than in normal control rats ($P < 0.001$). The nonspecific binding was identical in control (2.0%) and in 90% nephrectomized rats (2.1%) (Table VI). The displacement curves of ¹²⁵I-insulin by addition of increasing concentrations of unlabeled insulin in control and 90% nephrectomized rats are shown in Fig. 2. As shown, the binding of insulin was consistently reduced by 40–50% in the nephrectomized rats at all concentrations of insulin between 0.1 and 100 ng/ml. Scatchard analysis of the insulin binding data revealed curvilinear plots for both control and uremic rats which were parallel (Fig. 3). The total calculated insulin binding capacity in the nephrectomized rats (0.95 pmol/mg protein) was 45% lower than in control rats (1.75 pmol/mg protein). The relationship between changing receptor affinity for insulin and occupancy of receptor sites by the hormone is expressed by the "average affinity profile" (23) shown in Fig. 4. The shape of the average affinity profile in both control and uremic rats is consistent with a system displaying the phenomenon of negative cooperativity (23). The highest or "empty

site" affinity in uremic rats ($0.77 \pm 0.08 \text{ nM}^{-1}$) was not significantly different from that of control rats ($0.85 \pm 0.10 \text{ nM}^{-1}$). With increasing occupancy of receptors by insulin, the apparent K decreased to a similar extent in both groups of rats until the limiting low affinity state was reached which was again comparable in control and uremic rats.

Degradation of insulin by liver membranes. Table V shows the data on insulin degradation by liver membranes from control and uremic rats. Liver membranes from both control and 90% nephrectomized rats inactivated insulin to the same extent as measured by TCA precipitation and specific binding to liver membranes. These data indicate that decreased insulin binding in nephrectomized rats does not appear to be related to alterations in the insulin inactivation process in these membranes.

DISCUSSION

Insulin and glucagon play a central role in alterations of fuel homeostasis in many diseases. Uremia is char-

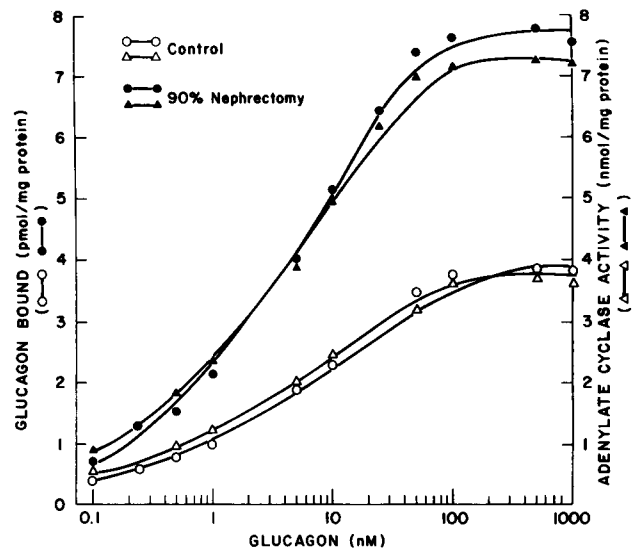


FIGURE 1 Correlation between glucagon binding and glucagon-stimulated adenylate cyclase activity in control and uremic rats (90% nephrectomy). In the glucagon binding studies, liver plasma membranes were incubated with the indicated concentrations of ¹²⁵I-glucagon under glucagon-binding assay conditions described in the text. Calculation of the amount of glucagon bound was based on the specific activity of labeled glucagon and the quantity of radioactivity bound per milligram of membrane protein. In the adenylate cyclase experiments, liver membranes were incubated with the indicated concentrations of glucagon under adenylate cyclase assay conditions described in the text. Adenylate cyclase activity is expressed as nanomoles of cyclic AMP generated/milligram protein per 10 min. The results of the binding and adenylate cyclase assay experiments are the mean of six individual animal experiments from each group of rats.

TABLE V
Degradation of ^{125}I -Glucagon and ^{125}I -Insulin by Liver Membranes*

Parameter	Degradation of ^{125}I -glucagon		Degradation of ^{125}I -insulin	
	Control rats	Uremic rats (90% nephrectomy)	Control rats	Uremic rats (90% nephrectomy)
	%		%	
TCA precipitation	28.0±5.0	30.0±6.5	24.4±6.0	20.5±5.6
Binding to liver membranes	41.0±4.0	45.0±6.0	39.5±7.0	36.2±5.8
Adenylate cyclase activation	39.6±4.0	41.5±5.0	—	—

* Labeled glucagon and insulin were exposed to liver membranes (0.2 mg/ml) as described under Methods. The degradation of labeled hormones was determined in the supernates isolated by centrifugation by analyzing three parameters: (a) precipitation by TCA; (b) specific binding to liver membranes; and (c) adenylate cyclase activation of liver membranes (used for ^{125}I -glucagon only). Tubes incubated under identical condition without membranes served as controls. Percentage of degradation is calculated as described under Methods. Each value represents the mean ± SE of eight experiments in each group.

acterized by hyperinsulinemia, insulin resistance, and hyperglucagonemia. In addition, recent studies from our laboratory indicate that there is increased sensitivity to glucagon-induced hyperglycemia in uremia (6). In the present study we examined the binding of ^{125}I -glucagon and ^{125}I -insulin to liver plasma membranes from 70 and 90% nephrectomized rats in order to explore the possibility that changes in glucagon and insulin receptors may account for glucagon hypersensitivity and insulin resistance in uremia.

The nephrectomized uremic rat model employed in the present study exhibited a moderate elevation of BUN and creatinine, hyperglycemia, hyperinsulinemia, and hyperglucagonemia (Table I), which are all characteristics of carbohydrate intolerance in uremic humans (1, 6). While heterogeneity of plasma glucagon has been noted in uremia, an absolute increment in true pancreatic glucagon (3,500 mol wt) has been observed in uremic humans as well as experimental animals (28). Thus, the nephrectomized uremic rat appears to be a good model to investigate glucose intolerance in uremia. The studies of ^{125}I -glucagon binding to hepatic membranes indicate that specific binding of ^{125}I -glucagon was approximately twofold higher in nephrectomized rats than in control rats

(Table III). Glucagon binding was somewhat higher in the 90% as compared to the 70% nephrectomized group. The findings with regard to recovery of plasma membrane and 5'-nucleotidase activity (Table II) indicate that the increment in glucagon binding cannot be explained by a systematic effect of uremia on the membrane purification procedure. Analysis of glucagon-binding data is complex and controversial (29, 30). Nevertheless, our data demonstrating a consistent increase in glucagon binding in nephrectomized rats at all concentrations of glucagon (Fig. 1) may be interpreted to indicate that the increase in glucagon binding in nephrectomized rats is mainly a result of an increase in the number of binding sites rather than a significant change in binding affinity.

The interaction between glucagon and its target organs has been shown to involve three closely related processes: glucagon binding, adenylate cyclase activation, and glucagon degradation (29). The finding of increased glucagon binding in livers from nephrectomized rats led us to investigate adenylate cyclase activity and glucagon degradation in liver membranes from the same groups of rats. We found that basal adenylate cyclase activity in uremic rats was 50% higher in uremic rats than in control rats.

TABLE VI
Influence of Nephrectomy on Insulin Binding to Liver Membranes*

Experimental group	^{125}I -Insulin bound		Specific binding of ^{125}I insulin
	Without unlabeled insulin	With 1,000 ng/ml unlabeled insulin	
	cpm		%
Control rats (n = 15)	37,865±6,775	3,015±490	23.2±4.2
90% nephrectomized rats (n = 15)	22,645±5,115	3,125±310	13.0±3.2

* Data are presented as mean ± SE for 0.2 mg membrane protein/ml of incubation medium. Total ^{125}I -insulin added per tube was ~150,000 cpm.

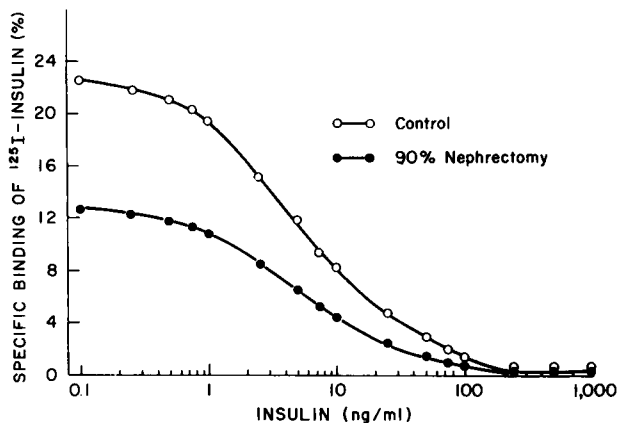


FIGURE 2 Binding and displacement of ^{125}I -insulin in control and uremic rats (90% nephrectomy). Liver plasma membranes (0.2 mg membrane protein/ml) were incubated with 0.2 ng/ml of ^{125}I -insulin and the indicated concentrations of unlabeled insulin in Krebs-Ringer phosphate buffer, pH 7.5 with 1% BSA. At the end of a 60-min incubation period at 30°C , ^{125}I -insulin bound to liver membranes was separated by centrifugation. Nonspecific binding (^{125}I -insulin bound in the presence of 1,000 ng/ml of unlabeled insulin) was subtracted from the total binding at each insulin concentration. Data represent the mean of eight individual animal experiments from each group.

As noted above, this observed difference in adenylate cyclase activity is unlikely to be a result of differences in the membrane purification procedure (Table II). Of even greater interest was the finding that glucagon-stimulated adenylate cyclase activity in uremic rats was twofold higher than in control rats. In contrast to glucagon-stimulated adenylate cyclase

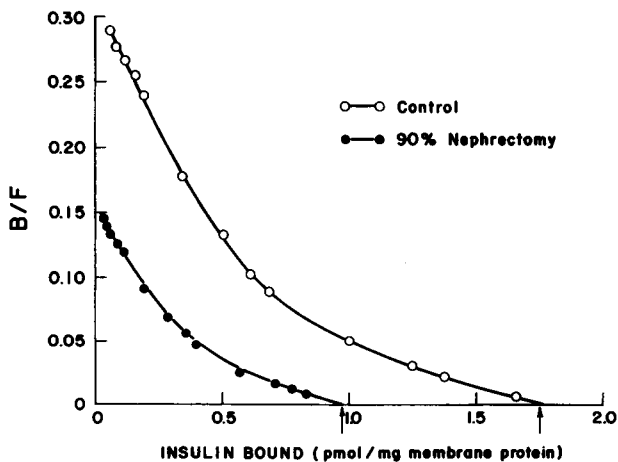


FIGURE 3 Scatchard analyses of insulin-binding data from control and 90% nephrectomized rats shown in Fig. 2. The ordinate, B/F , is the ratio of bound-to-free hormone and the abscissa represents the insulin bound (picomoles per milligram membrane protein). The intercepts at the abscissa represent the total concentration of receptor sites (R_0) and are indicated by the arrows.

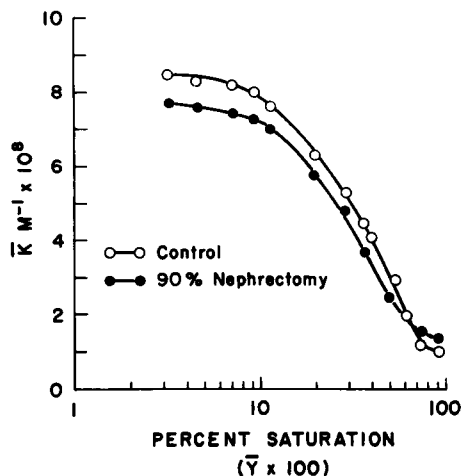


FIGURE 4 Average affinity profiles of ^{125}I -insulin binding to liver membranes from control and uremic (90% nephrectomy) rats. The average affinity (\bar{K}) is equal to $B/F/R_0 - B$. The percentage of the total concentration of receptor sites (R_0) that are occupied is given by $\bar{Y} \times 100$, where $\bar{Y} = B/R_0$. The data have been calculated from Scatchard plots in Fig. 3 according to the method of De Meyts and Roth (23).

activity, the stimulatory effect of sodium fluoride was not significantly increased in nephrectomized rats. These findings thus indicate that the augmented stimulation of adenylate cyclase by glucagon in uremic rats is not a consequence of a nonspecific increase in responsiveness of this system to all stimuli. Furthermore, the data indicate that augmented receptor binding of glucagon in uremia is accompanied by enhanced stimulation of postreceptor events. The importance of altered glucagon binding in hepatic cell metabolism in uremia is further underscored by the comparability of changes in hormone binding and adenylate cyclase activity over varying concentrations of glucagon (Fig. 1). However, it should be emphasized that the intracellular action of glucagon, as in the case of catecholamines (31) may not be dependent on changes in adenylate cyclase activity.

To examine the possibility that increased glucagon binding and adenylate cyclase activity may be a consequence of a significant decrease in glucagon degradation activity in liver membranes from uremic rats, we studied the glucagon inactivation process in these membranes. Our data indicate that glucagon degrading activity in uremic rats was similar to that of control rats (Table V). Thus, the observed increases in glucagon binding and adenylate cyclase activity in uremic rats do not appear to be related to alterations in the glucagon degradation process by liver membranes. These data are also consistent with the thesis that the marked reduction in the metabolic clearance of glucagon in uremia is a consequence of diminished

renal degradation rather than a result of changes in the hepatic degradation of this hormone (6, 28).

The mechanism(s) of increased glucagon binding and increased adenylate cyclase activity in uremic rats is not established. In this regard, it is of interest that recent studies provide evidence that alterations in hormone concentration may modulate its own receptors. For example, with insulin and progesterone, exposure to high concentrations of the hormone results in a loss of receptors in the target cells (32, 33). In contrast a high concentration of prolactin appears to induce its own receptor (34). It is conceivable that, in a like manner, hyperglucagonemia in uremia may induce its own receptors. On the other hand, Fouchereau-Peron et al. (10) have recently reported that hepatocytes isolated from starved rats, which are hyperglucagonemic, have decreased glucagon binding. Similarly, recent observations from our laboratory indicate that liver plasma membranes from starved rats have significantly decreased glucagon binding as compared to fed rats.² Alternatively, the increased glucagon binding and associated increase in glucagon-stimulated adenylate cyclase activity in nephrectomized rats may be a result of some metabolic abnormality associated with the uremic state, rather than a consequence of exposure of target cells to high concentrations of glucagon. Regardless of the mechanism involved, the current findings suggest that hypersensitivity to physiologic hyperglucagonemia observed in intact uremic patients (6) may be a consequence of augmented binding of this hormone to its receptor in liver membranes.

The results with ¹²⁵I-insulin clearly demonstrate a significant decrease in insulin binding by hepatic membranes in nephrectomized rats as compared to control rats (Fig. 2). Furthermore, our data on insulin degradation by liver membranes (Table V) indicate that decreased insulin binding in these rats is not a result of changes in the insulin degradation process, since membranes from uremic and control rats inactivated insulin to the same extent. Analysis of the insulin binding data by Scatchard plot indicates that decreased specific binding of ¹²⁵I-insulin in uremic rats is not a result of a decrease in the affinity of insulin receptors (Fig. 3). Since estimation of affinities of binding sites by curvilinear Scatchard plots may not be valid (25), the insulin binding data were also analyzed by the "average affinity profile" method of De Meyts and Roth (23). By that procedure, control and nephrectomized rats revealed identical affinity profile plots (Fig. 4). Thus, the analysis of insulin-binding data indicates that decreased insulin binding in uremic rats is mainly a result of a decrease in binding capacity rather than a significant change in binding affinity.

Regarding the pathogenesis of decreased insulin binding in uremia, it is of note that an inverse relationship between ambient insulin levels and insulin receptor concentration has been demonstrated in conditions such as obesity (7) and in experiments with cultured human lymphocytes (32). It is thus conceivable that decreased insulin binding observed in our uremic rat model is a consequence of hyperinsulinemia in these animals. It is also possible that some metabolic product in uremic plasma may affect insulin (and glucagon) binding. Irrespective of the mechanism involved, the fact that insulin and glucagon binding are oppositely affected excludes a systematic, nonspecific action of the uremic state on polypeptide hormone binding to liver receptors.

With respect to the significance of the decrease in insulin binding, a positive correlation between insulin binding and in vivo action of insulin has been reported in obesity (35). On the other hand, other studies have shown that changes in insulin binding and action may be divergent in starvation (36) and in diabetes (37). The current findings provide evidence that diminished insulin binding may be a contributory factor in the insulin resistance and glucose intolerance of uremia.

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