Dynamics of the glomerular filtration barrier - Physiological and pathophysiological aspects

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Dynamics of the glomerular filtration barrier
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The dynamic properties of the glomerular filtration barrier (GFB) are of fundamental importance for the understanding of the physiology and pathophysiology of microalbuminuria and proteinuric diseases. In the studies of this doctoral thesis the properties of the rat glomerular filtration barrier were investigated under resting conditions and following a number of challenges using highly sensitive gel filtration chromatography (HPSEC) detection of FITC-Ficol in serum and urine. This permeability model is extremely sensitive, and by using HPSEC, it was possible to measure extremely low concentrations of Ficol molecules in the urine. Under resting conditions the sieving coefficient (θ; filtrate-to-plasma concentration ratio) for Ficol 70Å was approximately 0.00001, and θ for albumin was found to be low, 0.0003 (or less). During increases in glomerular permeability θ for albumin and θ for Ficol 50-80Å increased in parallel, conceivably reflecting an increase in the number of large pores in the GFB. In study I, lipopolysaccharide (LPS) induced sensis produced increases in θ for albumin and θ for Ficol 50-80Å, at 120 min after LPS injection. In anaphylaxis there was a rapid permeability response already after 5 min which was reversed within 40 min. In study II, laparotomy, with or without muscle crush trauma, induced an increase in glomerular permeability after 5 min, which was to a large extent sustained after 60 min. Hyperglycemia (study III) induced an increase in θ for Ficol 50-80Å after 20 min, but not at 5 min, and after 60 min glomerular permeability was back to normal. The permeability increase seen after hyperglycemia at 20 min was totally abolished by a Rho-kinase inhibitor, indicating that the cytoskeleton of endothelial cells and/or podocytes may be involved. In study IV, high or low doses of ANP induced an increase in glomerular permeability for Ficol 50-80Å, reaching its maximum at 5 and 15 min. During ANP infusion (cf. congestive heart failure) there was a bimodal response, with a dip after 30 min, after which θ for Ficol 50-80Å again tended to increase. In this thesis the novel concept of a rapidly dynamic glomerular filtration barrier is introduced. During different challenges the size-selectivity of the GFB, rather than its charge-selectivity, was found to be subject to rapid and reversible alterations.

Key words: Glomerular filtration barrier, Glomerular permeability, Microalbuminuria, Albumin, Ficol, Sieving Coefficient (θ), Rats

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Dynamics of the glomerular filtration barrier
Physiological and pathophysiological aspects

Josefin Axelsson

Lund 2011

Clinical Sciences, Lund
Department of Nephrology
To mom and dad
Table of contents

Abstract 9
Original papers 11
Abbreviations 13
Aims of the thesis 15
Background 17
  The kidneys and their structure 17
  The glomerular filtration barrier 18
    Structure 18
    Properties of the GFB in some disease states 19
Tubular handling of proteins 20
Proteinuria 21
Molecular probes 22
Models of glomerular membrane permselectivity 23
  Solute and solvent flux across membranes 24
  Two-pore model of glomerular permselectivity 25
Some pathophysiological conditions provoking microalbuminuria 26
  Sepsis 26
  Anaphylactic shock 26
  Trauma 26
  Hyperglycemia 27
  Congestive heart failure 27
Material and methods 29
  Animals 29
  Surgery 29
  Molecular probes 29
Experimental procedures 30
  Paper I 30
  Paper II 30
  Paper III 31
  Paper IV 31
High pressure size exclusion chromatography (HPSEC). Ficoll\textsubscript{50-80A} serve as probes for the large pore equivalent 32
Abstract

The dynamic properties of the glomerular filtration barrier (GFB) are of fundamental importance for the understanding of the physiology and pathophysiology of microalbuminuria and proteinuric diseases. In the studies of this doctoral thesis the properties of the rat GFB were investigated under resting conditions and following a number of challenges using highly sensitive gel filtration chromatography (HPSEC) detection of FITC-Ficoll in serum and urine. This permeability model is extremely sensitive, and by using HPSEC, it was possible to measure extremely low concentrations of Ficoll molecules in the urine. Under resting conditions the sieving coefficient ($\theta$; filtrate-to-plasma concentration ratio) for Ficoll$_{70\text{Å}}$ was approximately $10^{-5}$, and $\theta_{\text{alb}}$ was found to be low, $3\times10^{-4}$ (or less). During increases in glomerular permeability $\theta_{\text{alb}}$ and $\theta$ for Ficoll$_{50-80\text{Å}}$ increased in parallel, conceivably reflecting an increase in the number of large pores in the GFB. In study I, lipopolysaccharide (LPS) induced sepsis produced increases in $\theta_{\text{alb}}$ and $\theta$ for Ficoll$_{50-80\text{Å}}$ at 120 min after LPS injection. In anaphylaxis there was a rapid permeability response already after 5 min which was reversed within 40 min. In study II, laparotomy, with or without muscle crush trauma, induced an increase in glomerular permeability after 5 min, which was to a large extent sustained after 60 min. Hyperglycemia (study III) induced an increase in $\theta$ for Ficoll$_{50-80\text{Å}}$ after 20 min, but not at 5 min, and after 60 min glomerular permeability was back to normal. The permeability increase seen after hyperglycemia at 20 min was totally abolished by a Rho-kinase inhibitor, indicating that the cytoskeleton of endothelial cells and/or podocytes may be involved. In study IV, high or low doses of ANP induced an increase in glomerular permeability for Ficoll$_{50-80\text{Å}}$, reaching its maximum at 5 and 15 min. During ANP infusion (cf. congestive heart failure) there was a bimodal response, with a dip after 30 min, after which $\theta$ for Ficoll$_{50-80\text{Å}}$ again tended to increase. In this thesis the novel concept of a rapidly dynamic glomerular filtration barrier is introduced. During different challenges the size-selectivity of the GFB, rather than its charge-selectivity, was found to be subject to rapid and reversible alterations.
Original papers

This thesis is based on the studies reported in the following papers, referred to in the text by Roman numerals (I-IV):


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Abbreviations

A/A₀  Diffusional restriction factor
A₀/ΔX  Unrestricted pore area over unit diffusion path length
aₑ  Stokes-Einstein radius
aₛ  Radius of a solid sphere
Cl  Clearance
CPM  Counts per minute
Da  Dalton
E. coli  Escherichia coli
FITC  Fluoroscein Iso-thiocyanate
GBM  Glomerular basement membrane
GFB  Glomerular filtration barrier
GFR  Glomerular filtration rate
IgG  Immunoglobulin G
IgM  Immunoglobulin M
Js  Solute flux
Jᵥ  Fluid flux
JᵥₓL/GFR  Fractional fluid flow through the large pores
Kₓv  Distribution coefficient
LDL  Low density lipoprotein
LMW  Low molecular weight
LPS  Lipopolysaccharide
Lₛₚ  Hydraulic conductance
MW  Molecular weight
nm  Nanometer
Pc  Capillary hydrostatic pressure
Pe  Peclet number (Jᵥ (1-σ)/PS)
Pi  Interstitial hydrostatic pressure
ΔP  Pₑ - Pᵢ
PKC  Protein kinase C
PS  Permeability-surface area product
PSD  Podocyte slit diaphragm
PTR  Proximal tubular reabsorption
$r_L$ Large pore radius
$r_p$ Pore radius
$r_s$ Small pore radius
TLR  Toll-like receptor
UAER  Urinary albumin excretion rate
Å  Ångström
θ  Sieving coefficient
$\alpha_L$ Hydraulic conductance accounted for by the large pores
$\lambda$  $a_e / r_p$
σ  Reflection coefficient
$\pi_c$ Osmotic pressure of capillary fluid
$\pi_i$ Osmotic pressure of interstitial fluid
$\Delta\pi$  $\pi_c - \pi_{Bow}$
1-σ  Restriction coefficient to convection
The overall aim of the present thesis was to gain further insight into the functions of the glomerular filtration barrier (GFB) in order to shed light on the mechanisms of microalbuminuria. How does the barrier behave during different pathological conditions and how does the permeability of the barrier change? The specific aims of the studies were:

**Study I** To investigate how the GFB is affected by systemic inflammation, induced by bacterial LPS, and to compare these changes with those occurring during acute anaphylaxis.

**Study II** To investigate the functional behavior of the GFB following acute trauma, i.e. in response to laparotomy, with or without skin dissection, and with or without muscle crush injury.

**Study III** To investigate the impact of acute hyperglycemia on the GFB and to elucidate if hypertonic mannitol or NaCl can affect the glomerular barrier. In addition, to investigate if a Rho-kinase inhibitor, by affecting the assembly of F-actin stress fibers in podocytes or endothelium, can impact upon the glomerular permeability during acute hyperglycemia.

**Study IV** To study the functional behavior of the GFB following infusion of ANP and hence to investigate if ANP can be responsible for the microalbuminuria seen during volume overload, such as in congestive heart failure.
Background

The kidneys and their structure

The kidneys are bean-shaped structures lying behind the peritoneum on each side of the lumbar vertebral column. The kidneys serve different essential functions, such as functioning as a plasma filter, thereby removing metabolic waste products and toxins, regulating the body fluid composition, regulating the acid-base and electrolyte balance and producing different hormones. The two kidneys comprise less than 0.5 % of the total body weight in man (300 g compared to 70 kg), but despite their low weight, receive approximately 20 % of the cardiac output.

Figure 1. The structure of the kidney.

The functional unit in the kidney is the nephron. Each kidney consists of approximately one million nephrons in man. A nephron consists of a glomerulus and tubular system, ending up in a collecting duct (Fig. 1). The glomerulus is a capillary tuft that is invaginated into and surrounded by the Bowman’s capsule, containing the Bowman’s space, into which an ultrafiltrate of plasma is produced via the glomerular filtration bar-
rier (GFB), by plasma sieving. A healthy adult filters roughly 180 L of plasma, so-called primary urine, every 24 hours across the GFB of its two kidneys. The filtrate is largely devoid of proteins, but otherwise has a composition similar to that of plasma (but affected by the Donnan equilibrium). From Bowman’s capsule the nephron continues with the tubule system. To maintain extracellular volume, electrolyte and acid-base homeostasis the tubules reabsorb (and control) the primary urine so that a final urine volume of roughly 1.5 L is excreted daily.

The glomerular filtration barrier

Structure

The glomerular filtration barrier is made up of three sequential layers; the glomerular endothelial cells, the glomerular basement membrane (GBM) and the podocytes with their foot processes² (Fig. 2).

The endothelial cells are the cells closest to the plasma side and on the abluminal (urinary) side lined by the GBM and the podocytes. They contain large fenestrations (diameter ~60-80 nm)³, holes that provide no restriction to the movement of water and small solutes but restrict blood cells. Endothelial cells are coated, on the plasma side, by a negatively charged glycocalyx⁴-⁵ consisting of glycosaminoglycans and proteoglycans. This layer may, by virtue of its negative charge, be important in restricting albumin and other negatively charged molecules from entering the GBM. The basement membrane, (0.3 μm thick) separates the endothelial layer from the epithelial layer. The GBM is basically a matrix of type IV collagen and laminin, crosslinked with negatively charged, sulphated glycoproteins and proteoglycans, such as agrin, perlecán and nidogen/en-
tactin$^6$-$^7$. The outermost layer of the glomerular filtration barrier is represented by the podocytes with their foot processes, enwrapping the glomerular capillaries. Foot processes have a contractile apparatus composed of F-actin filaments and non-muscle myosin, and the cell body is rich in microtubules and intermediate filaments$^8$. Between the foot processes are the filtration slits, which are interconnected by a thin structure, the slit diaphragm. The podocyte slit diaphragm (PSD) was first described by Rodewald and Karnovsky$^9$ and its presence has been confirmed by recent studies using modern techniques. A number of different proteins are known to span the filtration slits, such as nephrin, P-cadherin, podocin and Neph$^{10}$-$^{11}$. Of these, nephrin is the most important$^{12}$-$^{13}$. The proteins in the PSD play a critical role in coordinating podocyte structure and function$^{14}$ by inter-linking the F-actin cytoskeleton between individual foot processes. Conceivably this is important, because the cytoskeleton of the podocytes seem to maintain the function of the entire barrier. Glycoproteins with negative charges cover the podocytes, filtration slits and slit diaphragms$^{15}$.

Figure 3. A view of the glomerular barrier. In the left image a view from the inside of a fenestrated endothelium, and in the right image a view of the podocytes$^{16}$.

Properties of the GFB in some disease states

Ever since the discovery that a mutation in the gene coding for nephrin$^{17}$ can cause massive proteinuria (the congenital nephrotic syndrome of Finnish type), the podocyte slit diaphragm has been postulated to be the ultimate barrier for protein leakage. Many researchers are convinced that the PSD per se is an efficient sieve for macromolecules. However, the opinion that podocyte foot processes and the intervening slit diaphragm represent a scaffolding structure, which when damaged, causes the barrier (including the endothelium and the GBM) to lose its normal architecture and become leaky, is now gaining support. Studies using Angiotensin II on cultured podocytes has proposed that podocytes contract during this stimulation$^{18}$-$^{19}$. Because the actin-based cytoskeletal network in podocyte foot processes is linked to the basement membrane and slit diaphragm via various linker molecules, changes in the F-actin cytoskeleton in the foot processes may thus affect the structure and function of the entire glomerular barrier$^{18}$. A study using Angiotensin II and ANP$^{19}$ on cultured podocytes indicated contraction of podocytes after Angiotensin II, and podocyte relaxation after ANP, suggesting that ei-
ther change in the podocyte structure (contraction or relaxation) may cause changes in the glomerular barrier. Defects in any of the PSD proteins, with the possible exception of P-cadherin, can lead to the nephrotic syndrome including foot process effacement. For example, mutations in the gene encoding for α-actinin-4 can cause an inherited form of FSGS (FSGS type I) which leads to the nephrotic syndrome, and eventually, to renal failure. During this mutation, an abnormal assembly of actin is seen in the podocytes\textsuperscript{20}. Mutations in the type IV collagen gene, the backbone (together with laminin) of the GBM, may result in Alport's syndrome or, in its heterozygous form, the more benign “thin membrane disease” (benign familiar hematuria)\textsuperscript{6, 11}. However, the collagen network alone does not seem to be crucial for the size and charge selectivity of the barrier, since patients with Alport’s syndrome only suffer from mild proteinuria, besides having hematuria. Laminin may be of greater importance, since laminin β2 knockout mice display a severe nephrotic syndrome, without initial podocyte changes\textsuperscript{21}. During preeclampsia, the endothelial cells (GBM and podocytes are at least initially intact) have been postulated to be the culprit for the proteinuria as indicated by swelling of the endothelial cells, eventually leading to disruption of the barrier\textsuperscript{22}. It seems that any alteration, of at least one of the three layers of the barrier\textsuperscript{15, 23-25}, may cause a non-functional GFB, eventually resulting in proteinuria, and that normal function of the glomerular barrier requires the presence of three intact layers. The endothelial glyocalyx may represent the major charge barrier of GFB\textsuperscript{4, 15, 26}, since there is evidence that the negative charges of the GBM is of minor importance for charge selectivity of the glomerular filter\textsuperscript{27}. A previous study\textsuperscript{26} suggests that enzymatic removal of the endothelial glyocalyx, with e.g. hyaluronidase, markedly reduced the selectivity of the GFB to albumin, indicative of an effect of the charge barrier. However, unpublished (own) data indicate that there is an increase in the number of the large pores of the GFB after infusing hyaluronidase in rats, without any primary changes in the charge selectivity.

Tubular handling of proteins

Polypeptides and proteins are categorized in four different groups with respect to their size (i.e. molecular weight, MW): polypeptides of MW<10 kDa, proteins of low molecular weight (LMW) (10-44 kDa), proteins of intermediate MW (44-90 kDa) and high MW (>90 kDa). The kidney is mainly responsible for the metabolic clearance of circulating LMW proteins that are extensively filtered in the glomerulus and fully reabsorbed and catabolized by the proximal tubular cells and returned to the circulation as amino acids. With increasing protein size there is a steep decrease in their filterability, and for large proteins (albumin (a ~36 Å), orosumucoid (a ~30 Å), lactate dehydrogenase (a ~41 Å) and IgG (a ~55Å)) the kidney plays a minimal role in their clearance. Very high molecular weight proteins, i.e. α\textsubscript{2}-macroglobulin (a ~90 Å), IgM (a ~120 Å)
and LDL (a\textsubscript{2} -140-150 Å), are only found in the urine when the GFB is severely damaged, and then signal a worse prognosis of the underlying renal disease\textsuperscript{28}.

Proteins are normally reabsorbed efficiently in the proximal tubule system by two membrane bound receptors; megalin and cubulin, and the cooperating amnionless, resulting in almost protein-free urine\textsuperscript{29}. Megalin is an endocytotic receptor belonging to the low density lipoprotein (LDL) family and is heavily expressed in the kidney proximal tubule. It binds a number of different proteins, such as albumin, hemoglobin, myoglobin and lipoproteins. Cubulin is a large protein that is identical to the vitamin B\textsubscript{12} receptor found in the small intestinal mucosa. Cubulin share some ligands with megalin, such as albumin and immunoglobulins and is also seen to bind, for example, transferrin\textsuperscript{29}. Both the receptors play an essential role in the protein reabsorption in the proximal tubule\textsuperscript{30}. These proteins and the protein reabsorption process in proximal tubules have been described in detail elsewhere\textsuperscript{29-31}, and knockout mice for the different receptor proteins have been developed\textsuperscript{30}. The θ\textsubscript{alb} measured in megalin knock-out mice is low (2 × 10\textsuperscript{-4}) as further discussed below\textsuperscript{32}. In other experimental animal models, the use of lysine, by inhibiting the tubular protein reabsorption, has also made it possible to study the urinary leakage of large proteins in rats\textsuperscript{33}.

Proteinuria

Proteinuria designates the presence of elevated (nonphysiological) levels of proteins in the urine (>200 mg/24 h). During proteinuria the urine consists mainly of filtered plasma proteins and tubular Tamm-Horsfall proteins. The latter is a normal compound of urine produced mainly locally in the thick ascending limb of loop of Henle. Albumin is the main plasma protein, and an increased concentration of albumin in the urine is usually referred to as albuminuria. Even a small increase in the urinary excretion rate of albumin (UAER), microalbuminuria (30-300 mg/24 h), is an early feature of many renal diseases but is also an established marker of endothelial dysfunction or the general health of the vascular system. Microalbuminuria may also be a normal phenomenon, e.g. in strenuous physical exercise\textsuperscript{34}, or is seen in early diabetes, myocardial infarction, after trauma, and after knee and hip surgery\textsuperscript{35-39}. Low molecular weight proteinuria can occur in interstitial renal disease, such as in interstitial nephritis, lithium-nephropathy, or unspecifically, in chronic kidney disease (CKD) (interstitial fibrosis). Some rare renal syndromes can also present with tubular, low molecular weight proteinuria. These syndromes include for example Dent’s disease (CLC5-defect), Imerslund-Gräsbeck syndrome (cubilin deficiency), Lowe syndrome and cystinosis, all due to deficient proximal tubular reabsorption (PTR)\textsuperscript{29}.

Glomerular filtration of albumin is followed by tubular reabsorption (up to 98 %) and thus albuminuria reflects the net result of these two processes together. Glomerular proteinuria is caused by a defect in the GFB. Characteristic for this type of proteinuria
is that large plasma proteins that normally not are filtered, or only filtered to a limited extent, appear in the urine. Tubular proteinuria involves an impaired reabsorption of proteins by the tubular system. Smaller proteins that are freely filtered in the glomerulus and normally completely reabsorbed, can reach the urine when there is damage to the tubular system. Even for a normally functioning proximal tubule, tubular proteinuria can occur. Thus, when increasing amounts of proteins are filtered across the glomerular barrier they start to interfere with the normal tubular reabsorption of low molecular weight proteins, competing for the binding sites on the receptors in the tubular system. This is generally called “overload proteinuria”. Overproduction of various proteins, such as light chains in plasma in multiple myeloma, usually also produces a kind of overload proteinuria, “overproduction proteinuria” (cf. Bence Jones proteinuria). Low-molecular weight proteins are then, due to their increased plasma concentrations, filtered in higher amounts and when the tubular maximum is exceeded, they appear in the urine.

Molecular probes

The basic approach of permeability studies is to study how molecular probes, differing in physical and chemical properties, traverse biological membranes. The sieving coefficients (i.e. the steady state filtrate-to-plasma concentration ratios, $\theta$) obtained, tell us about the properties of the membrane. Proteins and polysaccharides have been extensively used as molecular probes to study the permselectivity of the capillary wall and the glomerular filter$^{40-43}$. Polysaccharides are polydisperse, inert (uncharged) and insignificantly reabsorbed by the proximal tubules, which makes them suitable for measuring glomerular permeability. Proteins have the main drawback that they are reabsorbed by the proximal tubules and they are usually charged, which makes their study difficult due to the complicated techniques needed to measure their glomerular $\theta$'s.

Ficoll is a neutral and highly branched, crosslinked polymer of epichlorohydrine and sucrose. As a synthetic molecule it is not to a significant extent reabsorbed by the tubular system$^{44}$ except from insignificant fluid phase endocytosis$^{44-45}$. Ficoll has been postulated to be a spherical molecule, with characteristics similar to those of a global protein. However, it is neither spherical nor as compact as a globular protein$^{44-46}$ (see below). Albumin is a compact protein molecule and the main plasma protein, produced by the liver. Native albumin has a net negative charge (-20), the Stoke-Einstein radius of albumin being 36 Å (its “real” shape is that of an ellipsoid of diameter ~40 Å and length ~140 Å) and its MW being 69 kDa.

The ability of a solute to pass the glomerular barrier depends on its size, shape, flexibility and charge. The GFB is size as well as charge selective, but the relative importance of its charge selectivity and its size selectivity is under intense debate$^{47}$. The view on charge selectivity of the glomerular barrier has mainly been based on studies using nega-
tively charged sulphated dextrans\textsuperscript{48-49} and on neutral vs. charged proteins of equivalent size\textsuperscript{47, 50-51}. In the classical studies from Brenner’s group, the glomerular permeability of negatively charged dextran was decreased compared to neutral dextran, and the permeability to positively charged dextran was increased compared to that of neutral\textsuperscript{48-49}. A number of studies have challenged these results\textsuperscript{50, 52-53}. It has been shown that negatively charged, sulphated dextran can bind to plasma proteins\textsuperscript{52} and cell membranes, and therefore show low glomerular sieving coefficients, whereas results using positively charged dextran could not be reproduced, or was attributed to conformational changes of the dextran molecules, or permeability changes of the barrier (which can be altered by polycations)\textsuperscript{48, 52, 54}. The glycocalyx with its negative charges is by many authors believed to be the main charge barrier of the glomerular filter\textsuperscript{15, 55}.

Renkin and Gilmore\textsuperscript{42} proposed already 30 years ago that polysaccharides, due to their extended structure, may be hyperpermeable across the glomerular filtration barrier compared to proteins. Asgeirsson \textit{et al.}\textsuperscript{56} confirmed these findings, and explained the hyperpemeability seen for polysaccharides by the fact that they have an extended molecular conformation, i.e. an increased “frictional ratio” and an increased flexibility. It is now generally accepted that neutral dextran (frictional ratio 2.1-2.8), a random coil polysaccharide, is hyperpermeable across the glomerular filter\textsuperscript{40, 57-58}. Bohrer \textit{et al.}\textsuperscript{57} furthermore showed that dextran is hyperpermeable relative to Ficoll. Furthermore the markedly elongated protein, bikunin, of the same SE-radius and negative charge (-20) as albumin but with a “frictional ratio” of 2.0, shows a 1000-fold higher permeability across the GFB than albumin (with a frictional ratio of 1.28)\textsuperscript{59}. Since Ficoll is expected to have a spherical shape, Ficoll has been accepted as the ideal probe for measuring glomerular permeability. However it has been shown that Ficoll is neither a completely spherical, nor an undeformable molecule\textsuperscript{44-46}. Ficoll seems to behave as an intermediate between a hard spherical molecule and a flexible random coil polysaccharide. The frictional ratio of Ficoll is 1.7 (to 1.9), which would render it slightly hyperpermeable across the GFB\textsuperscript{56}. It is evident, however, that Ficoll is hyperpermeable across the GFB only when the molecule radius exceeds 60 % of the pore radius ($\lambda$>0.6) or 70 % of the slit width. This indicates that Ficoll can be utilized as a probe (like neutral proteins) across the large pores of the glomerular filter (Ficoll 50-80 Å) but is hyperpermeable across the small pores (Ficoll 20-50 Å), because then $\lambda$>0.6.

Models of glomerular membrane permselectivity

A number of models are available to describe the solute and solvent transport across biological membranes. From experimental data in the form of fractional clearances (sieving curves) and prevalent hemodynamic conditions, a mathematical model is put forth to describe the membrane properties without being biased by hemodynamic effects. The most common models are the pore model and the fiber matrix model, which
in their simplest forms represent a single population of either pores or fibers that impose restriction to movement of molecules. They are made more complex by making the population of pores and fibers conform to a dual selectivity concept or to some statistical distribution, i.e. heteroporous or distributed (log-normal) pore models or fiber models. Charge can also be introduced into these models\textsuperscript{15}. The best model will minimize the difference between the experimental data and the theoretical model but still has to be rather simple.

**Solute and solvent flux across membranes**

Unhindered movement of molecules in solution occurs by diffusion and convection. Stokes law for the frictional coefficient of a spherical particle in solution in combination with the laws of diffusion derived by Fick and Einstein gives the solute diffusion coefficient ($D_s$):

\[ D_s = \frac{R \cdot T}{6 \pi \cdot N_A \cdot a_e \cdot \eta} \quad (1) \]

When traversing biological barriers, such as the glomerular filtration barrier, molecule transport is hindered and occurs at a slower rate than in free solution. This is described by the terms $A/A_0$ for molecules transported by diffusion and by $(1-\sigma)$ for molecules transported with convection\textsuperscript{60-61}. In the pore model, the formulas developed by Mason et al.\textsuperscript{60-62} is used, where restriction factors are a function of $\lambda$, the ratio of solute SE-radius ($a_e$) to pore size ($r_p$) and can have a value between 0 and 1.

\[ \frac{A}{A_0} = \frac{(1-\lambda)^{9/2}}{1-0.3956\lambda+1.0616\lambda^2} \quad (2) \]

\[ (1-\sigma) = \frac{(1-\lambda)^2[2-(1-\lambda)^2][1-\frac{2}{3}]}{1-2\lambda+\frac{2}{3}\lambda^2} \quad (3) \]

Based on irreversible thermodynamics, equations have been developed to describe solute ($J_v$) and solvent ($J_v$) movement across membranes\textsuperscript{63-64}.

\[ J_v = L_p S (\Delta P - \sigma \Delta \pi) \quad (4) \]

\[ J_s = J_v (1-\sigma) \bar{C} + P S \Delta C \quad (5) \]

where $L_p S$ represents the hydraulic conductance, $\Delta P$ the transmembrane hydrostatic pressure gradient, $\sigma$ the reflection coefficient of the membrane to the solute, $\Delta \pi$ the transvascular osmotic pressure gradient, $PS$ the solute permeability surface area product, $\Delta C$ the transmembrane solute gradient ($C_p-C_i$) where $C_p$ is the solute concentration in plasma and $C_i$ in the interstitium, $\bar{C}$ is the mean intramembrane solute concentration.
Integration of equation (5) across the membrane, between the boundary conditions \( C_p \) and \( C_i \) yields equation (6) (Patlak equation or the nonlinear global convection/diffusion equation):

\[
J_s = J_v (1 - \sigma) \frac{C_p - C_i e^{-Pe}}{1 - e^{-Pe}} \tag{6}
\]

Where \( Pe \) is representing the modified Peclet number. By dividing equation (6) by the plasma concentration of the solute an equation for solute clearance is obtained (7).

\[
Cl = J_v (1 - \sigma) \frac{1 - (C_i/C_p) e^{-Pe}}{1 - e^{-Pe}} \tag{7}
\]

Two-pore model of glomerular permselectivity

According to the two-pore theory, the equivalent small pores of the glomerular filter are approximately 37.5 Å in radius and the large equivalent pores are approximately 110 Å in radius, based on tissue uptake experimental data for neutral proteins\(^{65}\) and data from experiments in rats with lysine inhibited PTR\(^{33}\). The presence of negative charge in the small pores seems to almost totally exclude albumin from the small pore pathway. However, in large pores the charge effect is minor. The large pores are represented by only one large pore per \( 10^7 \) of the small pores.

Using a two pore model, there is convection dominated flux through the large pores where any diffusive contribution can be calculated to be negligible\(^{66}\). The main output from this model are: the small pore radius (\( r_s \)), the large pore radius (\( r_L \)), the fractional hydraulic conductance accounted for by the large pores (\( \alpha_L \)) and the total unrestricted pore area over diffusion path length (\( A_0/\Delta X \)). These parameters describe the membrane properties without being influenced by hemodynamic factors. The \( \alpha_L \) reflects the abundance of large pores in the glomerular filter and is calculated from the fractional GFR diverted through the large pores i.e. \( J_{vl}/\text{GFR} \). Both \( \alpha_L \) and \( J_{vl}/\text{GFR} \) can be mathematically obtained by extrapolating the “flat” part of the sieving curve for molecules with a radius larger than 50 Å back to the ordinate. \( \alpha_L \) is calculated according to equation 8, where \( P_{UF} \) represents the net filtration pressure.

\[
\alpha_L = \frac{J_{vl}/\text{GFR}}{\Delta \pi / P_{UF} (1 - \sigma_L) + 1} \tag{8}
\]

The small pore radius is mainly dependent on sieving data close to the region where there is a “knee” of the large pore and small pore curve, ~40-46 Å. \( A_0/\Delta X \) is the diffusive parameter essentially describing the surface area of the small pores.
Some pathophysiological conditions provoking microalbuminuria

Sepsis

Sepsis is a serious medical condition in which the bloodstream is overwhelmed with bacteria and/or bacterial toxins. This medical condition is characterized by a systemic inflammatory response state (SIRS), in the presence of an infection. In sepsis, the blood pressure drops due to vasodilatation and plasma loss from the circulation and major organ body systems, including the kidneys, may stop working properly, ending up in acute kidney injury (AKI) or multi-organ dysfunction (MODS).

The gram-negative bacterium, *E. coli*, is often found in the lower intestine of mammals. Most *E. coli* strains are harmless, but some strains of the bacteria can cause severe illness. The most common bacterial component implicated in initiating the septic syndrome is a cell wall molecule known as lipopolysaccharide (LPS) or endotoxin, which causes severe illness if entering the blood stream. The LPS molecule is composed of two biosynthetic entities, the lipid-A core and the O-polysaccharide. Most of the biological effects are due to lipid-A, which is seen to stimulate the mammalian immune system. LPS thus is a strong activator of various immune responses. It binds to TLR-4 receptors, thereby causing cytokine release (TNF-α, IL-6 etc.) and immune cell activation. Injection of LPS into animals can reproduce many of the manifestations of sepsis, including AKI.

Anaphylactic shock

Anaphylaxis is a severe, rapidly-progressing, whole-body, IgE-mediated reaction to a substance that has become an allergen. Mast cells in different parts of the body rapidly release histamine and other substances, such as 5-HT and heparin, in response to the allergen. Some drugs can cause this type of reactions, otherwise insect bites and food allergens are common causative agents. Signs of anaphylactic shock include low blood pressure, uticaria and, in the worst cases, swelling of the glottis, respiratory obstruction and death.

Trauma

Gross medical trauma refers to a serious or critical body injury, wound or shock, involving activation of various cascade systems in the body, including cytokine release, complement activation and activation of the coagulation cascade (eventually leading to disseminated intravascular coagulation, DIC). Body trauma may also involve massive
release of myoglobin, from the muscles, leading to “pigment-nephropathy” and AKI which is usually irreversible. However during the initial phases of gross body trauma, microalbuminuria may occur due to cytokine release (IL-6) and activation of immune cells.

**Hyperglycemia**

Hyperglycemia (high blood glucose) is the condition when excessive amounts of glucose circulate in the plasma. Normal blood glucose in fasting human is about 4-7 mmol/l. Blood glucose levels can rise up to 10 mmol/l normally without producing adverse permanent effects or symptoms. Diabetes mellitus is by far most common cause of chronic hyperglycemia. Chronic hyperglycemia or recurrent (post-prandial) hyperglycemia, with glucose levels moderately higher than normal, can produce a variety of serious complications, such as macrovascular and microvascular and renal damage. Acute hyperglycemia with blood glucose levels that are high (>20 mmol/l), is not uncommon in persons with uncontrolled type-II diabetes, or, in rare cases, in type I diabetes.

**Congestive heart failure**

Congestive heart failure is among the most common causes of hospitalization. Heart failure is a state when the heart is unable to pump enough oxygen rich blood to the rest of the body due to decreased cardiac myocyte contractility. Common causes of heart failure are myocardial infarction, ischemic heart disease and cardiomyopathy. Symptoms seen in heart failure are peripheral edema, dyspnea and venous congestion. On the cellular level, decreased contractility can be a result of cardiac hypertrophy reflecting alterations in the (transient) increases of Ca$^{2+}$ and/or expression of the contractile proteins in the myocytes. Atrial natriuretic peptide (ANP) is a peptide released from the cardiac cells (atrial myocytes) when stretched, i.e. in volume-overload, or in ischemia, i.e. during myocardial infarction. ANP is a potent vasodilator causing diuresis, and it thus enhances GFR and the renal excretion of Na$^+$ (i.e. natriuresis). By increasing capillary permeability ANP acts to lower the effective circulating blood volume and blood pressure.
Material and methods

Animals

The studies were performed in male Wistar rats. All experiments were approved by the Animal Ethics Committee at Lund University, Sweden.

Surgery

Anesthesia was induced by intraperitoneal (ip) injection of pentobarbital sodium (60 mg/kg) and maintained throughout the experiment by intra-arterial injections of the same anesthesia. The animal was placed on a heating pad to keep body temperature at 37°C. A tracheotomy was done to facilitate breathing (PE-240 tube). The tail artery was cannulated (PE-50 cannula) for continuous monitoring of mean arterial blood pressure (MAP) and for registration of heart rate (HR) on a polygraph (model 7B, Grass Instruments, Quincy, MA) and for administration of anesthesia. The left carotid artery was cannulated (PE-50) for blood sampling, and the right (and) left veins for infusion purposes. Access to the left urether was achieved through a small abdominal incision (6-8 mm). To increase urine production and facilitate the cannulation of the urether, Furosemide (Furosemid Recip, Årsta, Sweden) was administered in the tail artery. The urether was dissected free and a PE-10 cannula (connected to a PE-50) was inserted and secured. After the surgery, the animals were allowed to rest for 15-30 min.

Molecular probes

The exact amount of each tracer molecule used in each group of the experiments can be found in the respective paper. To measure the sieving properties of the GFB, the polysaccharide FITC-Ficoll was used. To deliver a broad distribution of molecular sizes, a mixture of Ficoll-70 and Ficoll-400 was used. The relationship between them was
Inulin was used to measure GFR, during the Ficoll sieving measurements and could be used as an “internal standard” to convert final urine Ficoll concentration into Bowman’s capsule (primary urine) concentration. All polysaccharides used were labeled with FITC by TdB Consultancy (Uppsala, Sweden).

I^{125} Human Serum albumin (RISA) for measurements of albumin clearance was obtained from Isopharma (Kjeller, Norway). {^{51}Cr-EDTA} was used to measure GFR during the whole experiments and was obtained from Amersham Bioscience (Buckinghamshire, UK).

Experimental procedures

The experimental procedures were different between the different studies and are explained in each study.

Paper I

Endotoxemia was induced by an intravenous (i.v.) bolus of lipopolysaccharide (LPS) followed by a constant i.v. infusion. Measurements were continued for 60 and 90 min, and in a separate group of animals, for 120 min. To induce anaphylaxis, rats were given 0.25 ml Dextran-70 i.v. as a bolus (Wistar rats are Dextran hypersensitive). Sieving measurements took place 5 and 40 min after the dextran injection in two separate groups of animals. FITC-Ficoll was infused during 20 min before measurement of Ficoll sieving coefficient and the measurement continued for 5 min. SHAM animals were given 0.9% saline mimicking the volume load in the experimental animal groups and followed for the same time as the experimental groups. Glomerular sieving of albumin was measured in the endotoxemia animals after 90 and 120 min as well as in the anaphylaxis groups and in the SHAM animals.

Paper II

Trauma was primarily induced by performing a laparotomy, ~50 mm long. The laparotomy was performed in the abdominal midline and along the linea alba of the abdominal muscle wall. This was the only trauma induced for two different groups of animals, followed for either 5 or 60 min. In an additional group, the skin was dissected away from m. rectus abdominis (following the laparotomy) bilaterally (~25 mm) at each side of the incision. This additional trauma was done in one group of animals followed for 60 min. In yet three additional groups of laparotomized animals (skin dissected away), crush injury was inflicted to the abdominal muscle by topically pinching the m.
rectus abdominis bilaterally by using a pair of hemostatic forceps according to Bansch et al. Muscle crush injury was induced either as a small injury (2×2 pinches) or a large injury (2×5 pinches) and followed for 60 min, and the latter one also for 5 min. The trauma was standardized by closing and opening the forceps for 10 s three times at each location. In the SHAM animals no laparotomy was done and these animals were followed for 5 and 60 min. FITC-Ficoll was infused 20 min before the measurement, and the measurement took place during 5 min. Sieving measurements for albumin took place right after the measurement for Ficoll in all of the experimental groups as well as for the SHAM animals. (The initial surgical trauma was followed in some experiments and yielded an initial increase in glomerular permeability which however, reversed in ~20 min.)

Paper III

Hyperglycemia was induced by i.v. administration of hypertonic glucose (40 %) in saline, given as a bolus and followed by i.v. infusion throughout the experiment. Blood glucose was “clamped” between 20-25 mmol/l. Blood glucose levels were measured approximately every 5 min and the glucose infusion adjusted to maintain the desired blood glucose level. Sampling of urine and plasma for Ficoll sieving measurements was performed at 20 min, or sequentially, at 5, 20 and 60 min. Hyperosmolarity was induced by i.v. infusion of either hypertonic NaCl or hypertonic mannitol to raise the plasma osmolarity by 14-15 mmol/l. Both hypertonic NaCl and hypertonic mannitol was given as a bolus followed by a constant infusion and urine and plasma samples for Ficoll measurements were taken 20 min after the start of the hypertonic insult. One separate group of animals was given Rho-kinase inhibition (Y-27632) during hyperglycemia (bolus and constant infusion) starting 5 min prior the hyperglycemia. Glomerular sieving measurements occurred 20 min after the induction of hyperglycemia. SHAM animals were given physiological saline as a bolus and constant infusion in a way mimicking the experimental interventions and were followed for 20 min, at which time the glomerular sieving measurements for Ficoll were performed.

Paper IV

Atrial natriuretic peptide (ANP) was given i.v. as a bolus followed by constant infusion throughout the experiment. Sampling for glomerular Ficoll sieving measurements was performed sequentially at 5, 15, 30, 60 and 120 min after starting the ANP infusion. In SHAM animals 0.9% saline was given, mimicking the volume load seen during the ANP experiments and sampling for Ficoll measurements performed at start 0-5 min and at 60 and 120 min.
High performance size exclusion chromatography (HPSEC). Ficoll serves as probes for the large pore equivalent

FITC-Ficoll in all the studies were size separated and their concentrations determined by high performance size exclusion chromatography (HPSEC). The plasma and urine samples were assessed using an Ultrasphere 500 column (Waters, Milford, MA) using a phosphate buffer (0.15 M NaCl, pH 7.4) as the mobile phase. The mobile phase was driven by a pump (Waters 1525). Fluorescence was detected at excitation wavelength 492 nm and emission wavelength at 518 nm (Waters 2475). The samples were loaded to the system by an autosampler (Waters 717 plus), and the system was controlled by Breeze software 3.3 (Waters).

The system was calibrated using narrow Ficoll and dextran standards. The polydispersity-corrected SE radii of the Ficoll standards were 70.2, 57.2, 45.1, 36.4 and 28.4 Å and the dextran standards were 164, 125.1, 105.6, 82.8, 63.7, 38.2 and 18.7 Å respectively. The proteins albumin, apoferritin, IgM, alcohol dehydrogenase and vitamin B₁₂ were also used to calibrate the column. These were detected with an absorbance detector (Waters 2487). The void volume ($V₀$) was measured with blue dextran ($2×10^6$ Da) and the total volume ($Vₜ$) with glycine (75 Da). From the results of the different measurements a distribution coefficient ($K_{av}$) was calculated according to formula 9:

$$K_{av} = \frac{(V_e - V₀)}{(Vₜ - V₀)}$$

where $V_e$ is the elution volume for each standard molecule. $K_{av}$ was plotted against the log of the SE radii of the respective standard molecule and fitted to a third polynomial.

The sieving coefficient for Ficoll was calculated by analyzing data from the HPSEC, i.e. the Ficoll concentration vs. elution time (translated into relative distribution volumes in the column of the different size Ficoll molecules), from urine and plasma ($C_{PF}$) samples from each experiment. The urine Ficoll concentration vs. the Stoke-Einstein radius curve was divided by the Inulin concentration to obtain the fractional primary urine concentration of Ficoll ($C_{UF}$). For each Ficoll radius the sieving coefficient was calculated by dividing $C_{UF}$ by $C_{PF}$.

Basically nearly identical methods are used throughout the four studies (study I-IV). Our HPSEC system enabled us to measure both molecular size as well as concentration of tracer molecules, and from these data to calculate $θ$ for a broad range of molecular sizes. Our permeability model is extremely sensitive and can measure extremely low concentrations of tracer molecules ($θ~10^{-5}$) in the urine, which requires a very stable baseline of a fine-tuned HPSEC system and at least four hours of buffer washout between each test sample.

By using the polysaccharide Ficoll in the studies, one can ignore the tubular reabsorption and charge effects which must be considered using proteins. The most favorable option would be to use FITC-labeled Ficoll and radiolabeled proteins (albumin)
together. In study I and II we were able to apply this principle, but due to insufficient radiolabeling of albumin, we were unable to use radiolabeled albumin in study III and IV. We have in all other studies showed a near perfect coupling between θ for albumin and that for Ficoll_{50-80Å} under conditions of increased permeability, and therefore find it reliable to use Ficoll_{50-80Å} as an indicator of glomerular permeability^{56, 71-72}. Both albumin and Ficoll_{50-80Å} pass, according to the two-pore model, the same pathway, namely “large pores” in the glomerular filter, and should therefore be interchangeable as probes for the large-pore equivalent. The presence of free label or albumin degradation products in study III and IV (unpublished observations) yielded very high θ values for albumin, particularly during normal conditions. Even in study I and II there may have been some free ^{125}I, and, to some extent, degraded albumin, which must have caused overestimation of the θ for albumin under control conditions. This is conceivably the reason why changes in θ are generally lower than the concomitant changes in Ficoll_{50-80Å}. It should be noted that the θ_{alb} values measured during control conditions (3×10^{-4} – 4.6×10^{-4}) represent “upper estimates” of the real θ_{alb}. In these respects, θ for Ficoll_{50-80Å} can be considered more reliable than θ_{alb} as probes for the large pore equivalent.

Radioactivity measurements

Radioactivity in urine and blood was measured using a gamma counter (Wizard 1480, LKP Wallac, Turku, Finland), correcting for radioactive decay and radioactive spill-over (^{125}I and ^{51}Cr).

The glomerular filtration rate (GFR) was measured as the clearance (Cl) of inulin or ^{51}Cr-EDTA according to the formula:

\[
Cl = \frac{(U_{Cr} \times V_u)}{P_{Cr}}
\]

where U_{Cr} is the concentration of ^{51}Cr-EDTA in urine, P_{Cr} the concentration of ^{51}Cr-EDTA in plasma and V_u the urine flow.

Tissue-uptake technique

Glomerular sieving coefficient for albumin was measured (paper I and II) using tissue-uptake technique^{73-74}. Radiolabeled (^{125}I) albumin (RISA) was injected i.v., after which the protein was allowed to circulate in plasma for eight minutes, during which time it dissipated within the extracellular space and filtered across the glomerular barrier. Thereafter, a whole body washout was performed via the carotid artery to remove any remaining tracer in the vasculature of the kidney during an additional eight minute period. The washout fluid was a mixture of equal amounts of 0.9% saline and heparinized
horse serum (SVA, Uppsala, Sweden). During the eight minute period, the breakdown of protein in the proximal tubular cells and the subsequent reabsorption of amino acids to the plasma is negligible, whereas a small fraction of the tracer will appear in urine. The filtered albumin will be found in the kidney cortex (medulla dissected away) and in the urine (the trichloroacetic acid precipitated fraction).

To calculate the glomerular protein clearance of albumin (ml/min), the mass transport (CPM/min) was divided by the plasma concentration of the tracer protein (CPM/ml). The glomerular sieving coefficient was then calculated by dividing the clearance by the simultaneously measured $^{51}$Cr-EDTA clearance (GFR).

The tissue-uptake technique has received critique in that it may underestimate the protein sieving coefficients. The critical part of this technique is, however, the washout-period and the quality of the radiolabeled tracer used. An incomplete washout or a bad quality of the tracer (denaturated protein) and a high fraction of free label ($^{125}$I) can only lead to overestimation of the sieving coefficients by contamination of tissue sample by free label or degraded proteins. High concentrations of free label thus yielded abnormally high $\theta$ values in tissue uptake studies under control (SHAM) conditions in study III-IV (unpublished data).

Another technical aspect is the eight minute time period from the injection of tracer to the start of the body washout, and hence, the cessation of the glomerular filtration of the filtered protein tracer. Because of marked dilution of RISA at eight minutes, it is reasonable to assume that filtration of albumin really stopped. However, at eight minutes, amino acids from the catabolized protein tracer may start to be reabsorbed to the circulation, which may lead to a slight underestimation of PTR.

The validity of the tissue-uptake technique is supported by the fact that the $\theta$ for albumin obtained agrees quite well with that obtained by independent techniques such as micropuncture$^{75}$ and lysine inhibition of PTR$^{33}$. Furthermore, patients with Dent’s disease, who have a congenital defect in PTR, show a similar glomerular $\theta_{\text{alb}}$ as that determined in rat with the tissue uptake technique$^{76}$.

**Transmission electron microscopy (TEM)**

In paper III transmission electron microscopy was done to investigate possible morphological changes in the glomerular barrier. Biopsies were taken from rat kidneys using a human (percutaneous) biopsy needle. Biopsies were immediately placed in fixative. After fixation, biopsies were rinsed in buffer and post-fixed before they were dehydrated and embedded. Ultrathin sections were then cut and placed on copper grid and stained with uranyl acetate and lead citrate. Sections were examined using a CM-10 transmission electron microscope (Philips Scientific, Eindhoven, The Netherlands).
Two-pore analysis

A two-pore model\textsuperscript{33, 62, 65} was used to analyze the θ data for Ficoll (mol. radius 15-80 Å). A nonlinear least-squares regression analysis was used to obtain the best curve fit, using scaling multipliers, as described in Lund \textit{et al.}\textsuperscript{65}.

Statistics

Values are expressed as mean ± SE, or as median and ranges. Differences between groups were tested using non-parametric analysis with Kruskal-Wallis test and post-hoc tested using Mann-Whitney U test. Bonferroni corrections for multiple corrections were made as needed. Significance levels were set at *p<0.05, **p<0.01 and ***p<0.001. All statistical calculations were made using SPSS 17.0 and 18.0 for Windows or Mac (SPSS, Chicago, IL).
Results

Endotoxemia and anaphylaxis alter glomerular permeability (study I)

In study I, increased sieving coefficients for Ficoll$_{50-80\text{Å}}$ and albumin after 120 min of endotoxemia were observed (Fig. 4a). This increased permeability to high MW Ficoll was, however, not seen at either 60 min or 90 min after the induction of endotoxemia. Figure 4b shows the time dependence of the changes in glomerular permeability following injection of endotoxin.

In the acute anaphylaxis group, followed for 5 min, there was significantly higher sieving coefficients for Ficoll$_{50-80\text{Å}}$ than in the SHAM-5 group. However, there was no significant difference between the group followed for 40 min and the SHAM group. Acute anaphylaxis thus caused a rapid, transient increase in glomerular permeability, completely reversible within 40 min.
Figure 5. The glomerular sieving coefficient vs. molecular radius of SHAM, 5 min of anaphylaxis and 40 min of anaphylaxis.

θ for albumin in the endotoxemia groups were measured at 90 and 120 min (Fig. 6a). After 120 min the θ was significantly increased vs. SHAM, but remained unchanged in the 90 min group. In the anaphylaxis groups, an increase in θ for albumin was seen both after 5 and 40 min (Fig. 6b). The increase at 40 min is not in agreement with the results from Ficoll_{50-80Å} and may be explained by an increased permeability of peritubular capillaries, but not in glomerular capillaries, during later phases of the 40 min of acute anaphylaxis.

Figure 6a and b. θ for albumin in the endotoxemia groups vs. SHAM (a.) and anaphylaxis groups vs. SHAM (b.). Significant increases can be seen for endotoxemia at 120 min vs. SHAM as well as for both the anaphylaxis groups vs. SHAM.
Effects of trauma on glomerular permselectivity (study II)

The study showed that there was an immediate increase in glomerular sieving coefficient for albumin and Ficoll\textsubscript{50-80Å} after a laparotomy, i.e. already after 5 min, and that this increase was sustained for at least 60 min. Adding skin dissection and/or muscle crush injury to the laparotomy did not further increase the glomerular sieving coefficient for Ficoll molecules of radius 50-80 Å (significantly). Again, there was a rapid and sustained increase in these groups of animals, with no significantly graded response relative to the magnitude of trauma induced. The two SHAM groups (followed for 5 and 60 min, in which no laparotomy was performed) showed almost unchanged and identical glomerular Ficoll sieving coefficients over time.

\textbf{Figure 7a and b.} Glomerular Ficoll θ vs. molecular radius for the different experimental groups exposed to laparotomy alone for 5 and 60 min (a.) and animals exposed for laparotomy followed by large muscle trauma for 5 and 60 min (b.).

The θ for albumin showed a significant increase at both 5 and 60 min compared to their respective SHAM groups (Fig. 8 and 9). As for Ficoll\textsubscript{50-80Å} there was no graded response relative to the trauma inflicted.
Figure 8. $\theta_{alb}$ in groups followed for 5 min, SHAM vs. trauma.

Figure 9. $\theta_{alb}$ for groups followed for 60 min. There was a significant increase in $\theta_{alb}$ between each of the trauma groups and SHAM.
Rapid, reversible increases in glomerular permeability due to hyperglycemia. Inhibition by a Rho-kinase inhibitor (study III)

Animals exposed to hyperglycemia were followed over time, at 5, 20 and 60 min (Fig. 10). Hyperglycemia caused significant increases in θ for large Ficoll molecules at 20 min, but the changes were completely reversible within 60 min. However, in contrast to the changes seen in anaphylactic shock and after laparotomy there were no changes in glomerular permeability observed already after 5 min.

Figure 10. θ of Ficoll 60, 70 and 80 Å as a function of time in animals receiving glucose. There was a complete reversal of the glomerular permeability increase noted at 20 min, at 60 min.

After 20 min, animals exposed to hyperglycemia showed an increase in θ for Ficoll\textsubscript{60-80Å} compared to SHAM. These results are in line with findings by Hempel et al.\textsuperscript{77}, using high concentrations of glucose in studies on endothelial monolayers. By contrast, animals receiving hypertonic mannitol or hypertonic NaCl showed no changes in θ for high MW Ficoll, similar to the SHAM group, indicating that the increase in plasma crystalloid osmotic pressure was not responsible for the θ increase. Furthermore mannitol is not known to induce permeability changes\textsuperscript{78}, rather the contrary. Thus an increased crystalloid osmotic pressure per se is not likely to be responsible for the increased glomerular permeability seen during acute hyperglycemia.

When giving glucose together with a Rho-kinase inhibitor (Y-27632), the glucose induced increase in glomerular permselectivity was totally abrogated, and the perm-
selectivity for this group was comparable to the SHAM animals. These results imply that acute hyperglycemia may involve changes in the F-actin cytoskeleton of either the endothelial cells or the podocytes, since RhoA and Rho-kinase are important players in the signaling of the cytoskeleton.

Figure 11a and b. Glomerular sieving coefficients for Ficoll 15-80 Å for animals injected with glucose, mannitol or NaCl vs. SHAM (a.) and during Rho-kinase inhibition (b.). During Rho-kinase inhibition, the permeability increase seen during glucose infusion alone, was completely abolished.

Morphological examination of kidney ultrastructure of animals receiving glucose vs. SHAM animals showed no significant changes (Fig. 12). All structures of the glomerular filter were investigated at high magnification, and no overt morphological changes with respect to endothelial cells, glomerular basement membrane or podocytes were found.

Figure 12. Morphological examination of SHAM animals (left) and animals exposed to hyperglycemia, followed for 20 min (right).
ANP induced rapid, cyclic alterations in glomerular permselectivity (study IV)

Figure 13. θ for Ficoll 70 Å for high dose ANP (top), low dose ANP (middle) and SHAM (bottom) as a function of time. Values are given as medians and ranges within the boxes. Hatched lines represent SHAM values.
Sequential measurements of animals intravenously infused with ANP demonstrated an immediate increase in θ for Ficoll \(_{50-80\,\text{Å}}\). Thus, already after 5 min there was a significant increase in glomerular permeability that was still evident after 15 min for both the low (30 ng·kg\(^{-1}\)·min\(^{-1}\)) and high dose (800 ng·kg\(^{-1}\)·min\(^{-1}\)) ANP groups (Fig. 13). For both the low and the high dose ANP group this increase was reversed at 30 min to near SHAM values. In the high dose ANP group there was a bimodal glomerular permeability increase. After the initial large peak (at 5 and 15 min) and a dip (at 30 min), there was a moderate increase at 60 and 120 min in θ for Ficoll \(_{50-80\,\text{Å}}\), which was statistically significant. For the low dose ANP group there was only a tendency of a glomerular permeability increase at 60 and 120 min (which was not statistically significant).

![Median curves for Ficoll 15-80 Å vs. molecular radius for low and high doses of ANP after 15 min vs. SHAM.](image)

**Figure 14.** Median curves for Ficoll 15-80 Å vs. molecular radius for low and high doses of ANP after 15 min vs. SHAM.
Discussion

Glomerular permeability under normal conditions

Though highly variable, normal UAER is about 5 mg to 30 mg daily in man. For 20 mg in UAER per day and 95 % of albumin being subject to proximal tubular reabsorption (PTR), 400 mg of albumin will appear in the primary urine daily. This corresponds to a $\theta_{\text{alb}}$ of $400 / 180 \times 40000 = 6 \times 10^{-5}$. This $\theta_{\text{alb}}$ is consistent with $8 \times 10^{-5}$ measured in patients with Dent’s disease, lacking PTR76, and with $2 \times 10^{-4}$ measured in megalin knock-out mice, also largely devoid of PTR32. It is also consistent with measurements in rats, in which the PTR was inhibited by lysine33 and conforms to the value given in the recent review by Haraldsson et al.15.

Contrary to this “glomerulocentric” view of glomerular proteinuria, Comper’s group79 suggests that the glomerulus produces nephrotic range proteinuria. Recent two-photon detection of fluorescently labeled albumin filtration into the Bowman’s space would indicate a $\theta_{\text{alb}}$ of 0.02, i.e. a value two orders of magnitude higher than the micropuncture assessed values43, 80 and results from recent tissue uptake studies65. The very high $\theta$ of albumin assessed by photometric detection may be due to free label, continuously produced during the measurements, and/or, partially, by quenching of fluorescence in blood by erythrocytes81.

The GFB as a dynamic barrier

As mentioned above the urinary excretion of albumin and other proteins is highly variable during 24 h and from day to day, both during normal (physiological) and pathophysiological conditions. Reversible increases in UAER, up to the range of microalbuminuria, can also occur during physical exercise34 and fever etc. The reason for this variability is poorly understood. Hemodynamic factors, i.e. variations in renal blood flow, and, hence in glomerular capillary pressure and GFR, may be partly responsible. Time-dependent variation in the proximal tubular reabsorption of urinary proteins is another tentative explanation. Finally, the phenomenon may be related to direct changes in glomerular permeability, either due to size or charge selective alterations.
From the present thesis, in which it was possible to assess glomerular permeability to macromolecules (Ficoll) in a time-dependent fashion in the absence of proximal tubular reabsorption and charge dependent effects, all during controlled hemodynamic conditions, it is evident that the GFB is not a static barrier. On the contrary, the GFB was found to be highly dynamic and to respond promptly, and mostly reversibly, to a number of different stimuli and challenges. This is a novel concept of the physiology of the GFB. The different patterns of acute glomerular permeability changes as a function of time, studied after a number of challenges in this thesis are shown in Figure 15.

All these changes are in the non-nephrotic, microalbuminuria range (20-200 μg/min in man) and are not a priori assumed to be linked to gross morphological changes of the GFB, such as foot process effacement, as seen in the nephrotic syndrome.

The different patterns of glomerular permeability seemed to be individual for each substance or challenge. The slow increase in glomerular permeability seen during endotoxemia, evidently parallels the many events taking place in the induction phase of the systemic inflammation response syndrome (SIRS), involving immune responses and release of cytokines. In the same study (study I), anaphylaxis induced a completely different permeability pattern, with a rapid permeability increase, that was reversed within 40 min. This rapid response reflects the rapid release of mediators, such as histamine, 5-HT and heparin, from mast cells and other immune cells, as a consequence of an acute IgE-mediated type I allergic response.
Body trauma induced a fast increase in glomerular permeability, that was still evident at 60 min after the injury. This rapid increase occurred more or less in all or none fashion, probably as a consequence of release of cytokines and not to myoglobin (unpublished observations). Laparotomy alone was sufficient to induce marked increase in permeability, but added skin dissection and/or muscle trauma did not increase glomerular permeability further. The response to body trauma may be mediated by activation of immune cells and the release of cytokines, predominantly interleukin (IL)-6 and IL-10. Activated leukocytes may also adhere to the endothelium and cause local damage by releasing agents such as reactive oxygen species (ROS).

The transiently increased GFB permeability during acute hyperglycemia had a delayed pattern, similar to what has been observed in hyperglycemia induced permeability changes in endothelial monolayers in vitro. Sequential measurements during hyperglycemia demonstrated a peak after 20 min, while the permselectivity was comparable to the SHAM animals both at 5 and 60 min. The mechanisms of an increased glomerular permeability in hyperglycemia will be discussed separately.

High and low doses of ANP showed a rather similar pattern of glomerular permeability. For high dose ANP there was a rapid permeability increase already at 5 (and 15) min. However the ANP induced glomerular leakage seemed to be biphasic, with an initial increase at 5 and 15 min followed by a dip at 30 min, but a moderate subsequent increase at 60 and 120 min. The first permeability peak of ANP was actually quite similar to that seen during anaphylaxis, with a rapid increase, followed by a decline in glomerular permeability within 30-40 min. The direct assessment of glomerular permeability in study IV supports the concept that ANP increased glomerular permeability by direct effects on the glomerular filtration barrier, which did not involve charge dependent changes. ANP (and BNP) acts on the ANP/BNP receptor, guanylyl cyclase-A (GC-A). ANP receptors are seen on podocytes, mostly localized to the foot processes. It is evident that ANP might produce podocyte relaxation and it is thus speculated that ANP may alter the shape of the podocyte. These changes apparently involve changes in the F-actin cytoskeleton, and hence the tension the podocytes exert on the GBM, thereby affecting the permeability of the entire GFB.

Microalbuminuria

Microalbuminuria is an established marker of endothelial dysfunction, but can be found normally and in several renal diseases. Microalbuminuria may be an early sign in uncontrolled diabetes mellitus. Microalbuminuria is as common feature following the systemic inflammation response syndrome (SIRS) and other acute inflammation states, but also after physical exercise. Microalbuminuria is however not seen during anaphylaxis due to the transient nature of the glomerular permeability changes (study I). Several investigators have shown the presence of microalbuminuria after serious
trauma, thermal injury and after operations, such as after knee and hip surgery. It has not been established whether the microalbuminuria is due to a glomerular dysfunction, due to either size-selectivity or due to charge selectivity defects, or to a decrease in the tubular reabsorption of albumin. Nergelius et al. showed a maximal increase in urinary albumin (and IgG) excretion in man one day after surgery, while protein HC showed a maximal increase in the urine two days after surgery, indicating glomerular leakage immediately after surgery and a defect in tubular reabsorption appearing after 24h. During heart failure, often associated with myocardial infarction and ischemic heart disease or cardiomyopathy, the presence of microalbuminuria (and sometimes overt proteinuria) has been shown by different investigators.

**Fundamental behavior of the two-pore model**

The two-pore model has been used throughout the studies (study I-IV) to model the properties of the glomerular filtration barrier and the filtration across the barrier. The radius of the small pore was fairly consistent throughout the studies, and changes in this parameter were uncommon in-between and between the experimental and the SHAM groups. The morphological correlate to the “small pore equivalent” is conceivably the meshes in a rather regular network of molecules (laminin and collagen) in the GBM, and possibly, in the gel-like structure of the endothelial glycocalyx. The large pores may represent very rare (1/10⁷ of the small pores) irregularities in this meshwork. Whereas an increase in the number of large pores was the regular response when the permeability of the GFB increased, the large pore radius tended to increase in some of the experimental groups, i.e. for low dose ANP, during hyperglycemia and during the rapid increase in glomerular permeability during anaphylaxis. During trauma there was also a tendency of increase in large pore radius. This may reflect an opening of large shunts within the GFB (a third pore), in excess of an increased number of large pores (radius 110-120 Å).

According to the two-pore model albumin is excluded from the small pore pathway by size-selectivity and due to a negatively charged glomerular filter. Due to the negative charges of albumin it thus behaves similar to Ficoll which according to the two-pore theory, solely pass through the large pores. By contrast neutral albumin can, due to its lack of negative charges, pass the small pore pathway, explaining its much higher glomerular permeability than albumin. Ficoll is hyperpermeable across the GFB compared to native albumin and will overestimate the radius of the small pores.

For stable GFR, the Jv/GFR is a more stable and direct parameter than αL. Jv/GFR and αL are mathematically obtained by interpolating the rL-curve (for molecules >50 Å in radius) back to the ordinate scale (to 0 Å). This imparts some uncertainty, if rL is altered. If there is an increment in rL, αL and Jv/GFR tend to be underestimated, and if there is a decrease in rL, they tend to be overestimated. Both αL and Jv/GFR are in
study I-IV seen to increase, when permeability is affected, correlating with the increase in θ for Ficoll\textsubscript{50-80Å} and θ\textsubscript{alb}, indicating the presence of an increase in the number of large pores in the GFB.

Possible mechanisms of increased glomerular permeability

The rapid response of the GFB to permeability enhancing stimuli and the (near) complete reversibility of this response within 30-40 min is reminiscent of the cyclic changes that occur in endothelial permeability in response to e.g. histamine, bradykinin or substance P. These alterations are dependent upon the contractile machinery of the endothelium, i.e. F-actin and non-muscle myosin, and are thus known to be Ca\textsuperscript{2+} dependent and rapidly reversible (max 10-15 min), i.e. cyclic, and also subject to tachyphylaxis\textsuperscript{87-88}. After the first bout of permeability increase, the endothelium in rat hindquarter muscle capillaries was found to be refractory for another hour, but still responded to markedly higher doses within that time frame\textsuperscript{87}.

Similar to the endothelial cells, podocytes are not static, but contain a contractile system. The contractile system contains actin, myosin and α-actinin-4, among other molecules. Via α-actinin-4 and CD2AP the contractile system is linked to the podocyte slit diaphragm (PSD) and via a α3β1-integrin and a dystroglycan complex it is linked to the GBM\textsuperscript{89}. Although PSD is not believed to be the critical size-selectivity barrier\textsuperscript{65, 90}, the contractile system seems to be of importance to maintain the GFB intact, when e.g. challenged by increased transmural pressure. Alterations in the podocytes may therefore be responsible for secondary changes in the size-selectivity of the GBM and the endothelium.

Hyperglycemia

Acute hyperglycemia in cultured aortic porcine endothelial cell monolayers, induced a rapid increase in monolayer permeability\textsuperscript{77}. The effects began within 20 minutes, reached a maximum after 30 minutes and returned to control values within 100 minutes. Administration of a protein kinase C (PKC) inhibitor counteracted the acutely increased endothelial monolayer permeability mediated by hyperglycemia\textsuperscript{77}. Several investigators support the notion that PKC is an important mediator of hyperglycemia-induced permeability \textit{in vitro}, suggesting that PKC may be a mediator of hyperglycemia induced hyperpermeability of the GFB. PKC inhibitors are, however, in general too unspecific \textit{in vivo}. Another investigation has shown that hyperglycemia may prime monolayers of cultured bovine glomerular endothelial cells to produce endothelial cell-to-cell disruptions and endothelial cell contraction, and thereby, paracellular holes when co-exposed to e.g. a tromboxane A\textsubscript{2} (TXA\textsubscript{2})- analogue\textsuperscript{91}. The Rho-kinase inhibi-
tor Y-27632 abrogated the increased permeability induced by the TXA₂ analogue during hyperglycemia in a manner similar to what has been shown in study III. In spite of the increased glomerular permeability following 20 minutes of hyperglycemia, there were no morphological changes observed in the glomerular filtration barrier investigated using TEM.

Podocytes have a highly evolved GLUT glucose transport system⁹² and are one of the cell-types, beside muscle cells and adipocytes, which have been shown to be insulin-sensitive⁹³. After i.v. insulin infusion (unpublished observations), we found no effect of insulin on the rat glomerular permeability. The glucose-lowering effect of the human and porcine insulin used (canine insulin was no longer available), was, however low under the conditions of marked hyperglycemia, which raises some questions of the reliability of these experiments. Furthermore there is no obvious support in the literature that insulin should increase the permeability of the GFB.

A few days of sustained hyperglycemia (20 mM) exposure of cultured endothelial cells has been shown to permanently alter cell structure, with centralization of actin filaments in the endothelial cells⁹⁴. Hyperglycemia for 72 hours has been shown to induce apoptosis and foot process effacement of cultured podocytes, and ROS generation has been shown in podocytes after six hours of hyperglycemic exposure⁹⁵. Furthermore glomerular permeability was found to be unaltered in rats exposed to hyperglycemia for three weeks, but not for nine weeks⁷². This is in contrast to the rapid, reversible alterations found in study III.

**Rho-kinase and glomerular hyperpermeability during hyperglycemia**

The RhoA/Rho-kinase pathway plays an important role in the structure and function of various kidney cells including tubular epithelial cells, mesangial cells and podocytes⁹⁶. Although the many aspects of signaling upstream and downstream of RhoA/Rho-kinase is not understood, it has become evident that RhoA/Rho-kinase pathway is involved in a variety of diseases⁹⁷.

Dynamic rearrangements of the cytoskeleton and cell adhesion are required for various cellular processes such as shape changes and migration. Rho-kinase can exert its actions by the signal molecule RhoA, activating the Rho-kinase by phosphorylating, and thereby, inactivating myosin phosphatase. It is assumed that Rho-mediated inactivation of myosin phosphatase favors myosin light-chain (MLC) phosphorylation in the presence of MLC kinase activity. Conversely, when Rho is inhibited, MLC phosphatase activity increases and MLC phosphorylation is favored. Rho-kinase is an important mediator not only of vascular contraction but also of actin cytoskeleton reorganization, cellular morphology, motility, adhesion and proliferation⁹⁶. With respect to podocyte morphology, some data support that RhoA has a “stabilizing” effect on the F-actin cytoskeleton⁹⁸ while in endothelium RhoA seems to increase F-actin contractility. Our data and the data from Nobe *et al.*⁹¹ do not support the notion that RhoA/Rho-kinase system acts as a “stabilizing podocyte factor”. On the contrary, this system seems to be
involved in the active rearrangements of the F-actin system conceivably occurring in hyperglycemia.

Figure 16. Signalling pathway of RhoA/Rho-kinase. MBS – myosin binding subunit of myosin phosphatase, cat – catalytic subunit of myosin phosphatase and MLC – myosin light chain

Hemodynamic parameters

It has been demonstrated that the sieving coefficients for Ficoll$_{13-43\text{A}}$ are reduced when GFR is raised from initially low values to higher (normal range) values in hydropenic rats$^{90}$. This finding contradicts the notion that the PSD would be the critical sieving barrier in the GFB, in which case the opposite would have occurred. The same study also showed a tendency toward a reduction in θ for large Ficoll molecules (>60-70Å) with increased GFR. This study supports two previous studies investigating θ vs. GFR$^{65,99}$, indicating that there is a decrease in θ, for small endogenous proteins and albumin, following increases in GFR. This behavior reflects the increased importance of filtration, as compared to diffusion, (i.e. an increased Peclet number) when GFR is increased.
A parallel increase in $A_0/\Delta X$ together with an increase in GFR will leave the sieving curve unchanged, since both the parameters are changed in the same direction (Peclet number unchanged). The same is true, if both parameters decrease. If a decrease is seen in GFR or an increase occurs for $A_0/\Delta X$, the sieving curve would however, become steeper (a sharper cut-off), while the opposite occurs (i.e. the sieving curve would flatten) when GFR is increased or $A_0/\Delta X$ reduced. It is then important that the Peclet number (essentially GFR over $A_0/\Delta X$) is preserved for all challenges delivered.

Mean arterial pressure (MAP), heart rate and glomerular filtration rate was measured continuously during the experiments in all studies. A summary of average MAP and GFR, respectively, for the four different studies is shown in Figure 17 and 18 respectively.

Figure 17. MAP of the four different studies (Study I-IV).
Figure 18. GFR of the four different studies (Study I-IV).

Even though great variability was seen for MAP and/or GFR during the experiments, i.e. in LPS induced sepsis, in anaphylactic shock, in large body trauma and in high dose ANP, measurements of $\theta_{\text{Ficoll}}$ and $\theta_{\text{alb}}$ were done during rather stable hemodynamic conditions. The significant decrease in MAP during high dose of ANP was not seen during infusion of low dose ANP. Furthermore, whereas there was a decrease in MAP for the high dose of ANP, the GFR was still rather stable (conceivably due to precapillary vasodilatation and postcapillary vasoconstriction). Even though the MAP and GFR varied in some of the other experiments, the $\theta$ measurements were done when MAP and GFR showed stable values, i.e. close to the initial values.
Conclusions

- The normal permeability of the rat GFB is very low. The ratio of the albumin concentration in the glomerular ultrafiltrate over that in plasma ($\theta_{albumin}$) was only $3 \times 10^{-4}$ during control conditions and $\theta$ for Ficoll$_{50-80\text{A}}$ was even lower.

- The GFB is highly dynamic and can respond rapidly, and mostly reversibly, to different stimuli and challenges, such as sepsis, anaphylactic shock, trauma, acute hyperglycemia and ANP infusion (cf. congestive heart failure) to cause microalbuminuria.

- Changes in glomerular permeability can occur without visible changes in the structure of the glomerular barrier. These changes are thus different from those occurring in nephrotic range albuminuria, in which foot process effacement is a regular phenomenon.

- The glomerular permeability changes studied seem to reflect a real decrease in size-selectivity, due to increases in the number of large pores in the GFB, and are not linked to changes in charge or to changes in proximal tubular protein reabsorption.

- Hyperglycemia induced glomerular hyperpermeability was transient and could be abrogated by Rho-kinase inhibition, suggesting involvement of the cellular F-actin cytoskeleton in this response.
Populärvetenskaplig sammanfattning (Swedish summary)


Den minsta funktionella enheten i njuren kallas nefron (Fig. 1) och består i dess första del av ett kärlnystan (glomerulus) med en omgivande kapsel, Bowmans kapsel. Glomerulus utgörs av små blodkärl, så kallade kapillärer. Kapillärers unika egenskaper gör det möjligt för blodplasma att filtreras över kapillärväggen, ungefär som passagen av vatten och kaffepartiklar i kaffebryggarens kaffefilter. Den filtrerade plasma som passerat kapillärväggen (äggvitefritt plasmavatten) bildar primärurin. Njurens filter utgörs av tre lager: endotelcellerna, det glomerulära basalmembranet (GBM) och podocyterna (Fig. 2). Endotelceller finns närmast blodet och har ett slemartat ytskikt som kallas glykokalyx (med negativa laddningar). Basalmembranet är uppbyggt av ett nätverk av trådliknande molekyler, såsom laminin och kollagen. Podocyterna omsluter kapillärrna och bildar så kallade filtrationsspalter mellan sina fotutskott. Sannolikt spelar alla tre lager roll för att hålla filtret tätt och för att njuren ska fungera korrekt. En störning i något av dessa lager, oavsett i vilket, leder till att protein filtreras ut i urinen. Med hjälp av porer i njurfiltret, små och stora, separeras stora molekyler från vatten och salter från plasma och blir till primärurin.
Det finns en svårighet med att studera proteinuri, vilken består i att de proteiner som filtreras över kapillärväggen i njurens filter nästan fullständigt återupptas tidigt i nefronet (proximala tubuli). Därför använder vi oss av en icke kroppsegen substans när vi studerar njurens filter; icke kroppssegna substanser återupptas nämligen nästan inte alls. Vi använder oss av en polysackarid (sockerart) som kallas Ficoll för att mäta njurens genomsläpplighetsegenskaper. Det finns skillnader mellan att använda polysackarider och proteiner. Proteiner är ”härda”, kompaka, och i många fall runda, medan polysackarider har en lägre täthet och är mer flexibla.


I den första studien (study I) undersöktes hur njurfiltrets genomsläpplighet i rätta förändras vid blodförgiftning orsakat av ett gift från coli-bakterier (lipopolysackarid, LPS), samt vid allergisk chock (anafylaktisk chock). Studien visade att blodförgiftning under 120 min orsakar en ökning i sievingkoefficient för Ficollmolekyler i storlek 50-80 Å. Hos djur som erhöll LPS och följdes under bara 60 och 90 min sågs ingen ökning av genomsläppligheten för Ficoll. Radioaktivt albumin visade överensstämmande resultat med Ficoll. Anafylaktisk chock orsakades genom att ge djuren polysackariden dextran, vilken i rättor framkallar ett chocktillstånd. Efter 5 min påvisades en förhöjd genomsläpplighet för Ficoll,50-80Å, som tecken på öppning av ”stora porer” i njurfiltret, som helt gick tillbaka efter 40 min. Mätningar med radioaktivt albumin påvisade dock ett ökat njurbarksupptag av albumin vid båda tidpunkterna. Ett ökat upptag av albumin till njurbarken vid 40 min kan bäst förklaras med att andra kapillärer än glomerulus- kapillärer i njuren har fått en ökad genomsläpplighet för albumin vid den framkallade chocken även efter det att glomerulus kapillärer ”stängts”.

Studie nummer två (study II) fokuserade på den glomerulära genomsläppligheten efter kroppsskada (trauma) med eller utan krosskada. För att framkalla ett trauma gjordes ett medellinjessnitt i buken på djuret (laparotomi). Utöver detta trauma gjordes sedan på vissa djur en krosskada genom att krossa främre bukmuskeln på höger och vänster sida med en grov peang. Resultaten visade att en öppning av buken var tillräcklig för
att ge en kraftig ökning av genomsläppligheten för Ficoll\textsuperscript{50-80Å}. Tillägg av krosskada ökade inte ytterligare genomsläppligheten för Ficoll\textsuperscript{50-80Å}. Dessa resultat gällde vid såväl 5 som 60 min efter orsakat trauma. Studier med radioaktivt albumin påvisade en ökad sievingkoefficient vid laparotomi samt laparotomi med extra krosskada vid båda tidpunkterna. Poranalysen påvisade ett ökat antal stora porer i njurens filter efter trauma, såväl som en ökning i dess storlek.

I studie nummer tre (study III) studerades njurens genomsläpplighet för Ficoll vid högt blodsocker. Högt blodsocker orsakades i djuren genom att ge dessa en stark druvsocker (glukos) - blandning. Tjugo minuter efter blodsockerhöjning (>20 mmol/l) sågs genomsläppligheten för Ficoll\textsuperscript{50-80Å} öka i njurens filter. Men redan efter 5 min och efter 60 min sågs ingen ökning. Stark manitollösning (en annan sockerart som liknar glukos) eller en stark saltblandning innehållande natriumklorid (NaCl) gavs till två grupper av djur. Resultatet visade att genomsläpppligheten inte ökade för Ficoll\textsuperscript{50-80Å} under dessa förhållanden. Vi undersökte också om en specifik signalmolekyl-hämmare (Rhokinashämmare) kunde motverka den ökade genomsläppligheten vid ett blodsocker över 20 mmol/l. Om vi gav djuren denna substans samtidigt som vi orsakade högt blodsocker sågs ingen ökning i genomsläppligheten vid Ficoll\textsuperscript{50-80Å}, vilket visar att vår utvalda signalmolekyl spelar en viktig roll för en ökad genomsläpplighet över njurens filter vid högt blodsocker. Eftersom Rho-kinas kan påverka cellers förmåga att ändra form, tycks den ändrade permeabiliteten bero på cellförändring. Poranalysen visade ett ökat antal stora porer i njurens filter 20 min efter givande av högt blodsocker samt en ökning av de stora porernas storlek.

Mikroalbuminuri är en vanlig företeelse vid hjärtsvikt. I studie nummer fyra (study IV) studerades hur ANP (atrial natriuretic peptide), som frisätts hos patienter med hjärtinfarkt eller hjärtsvikt påverkar njurens filter. ANP gavs till djuren och den glo-merulära genomsläppligheten för Ficoll studerades under 120 min med sekventiella mätningar vid 5, 15, 30, 60 och 120 min. ANP gavs i antingen en låg eller en hög dos. Resultatet visade att ANP, både i låg och hög dos, orsakar en ökning av genomsläppligheten för Ficoll\textsuperscript{50-80Å}, med start vid 5 min och maximal effekt efter 15 min. Vid 30 min återgick genomsläppligheten till det normala, för att sedan återigen sakta öka vid 60 och 120 min. Dessa resultat talar för att ANP kan vara ansvarigt för den mikroalbuminuri som ses hos patienter med hjärtsvikt eller hjärtinfarkt.

Det primära syftet med avhandlingen är att försöka förstå bakgrunden till äggvita (albumin) i urinen vid en rad olika sjukdomstillstånd som blodförgiftning, hjärtsvikt, anafylaktisk chock och efter trauma.
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References


Appendix – Study I-IV

"The beginning of knowledge is the discovery of something we do not understand"

Frank Herbert
Paper I
Effects of early endotoxemia and dextran-induced anaphylaxis on the size selectivity of the glomerular filtration barrier in rats

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MICROALBUMINURIA, I.E., JUST moderately increased urinary albumin excretion rates (20–200 µg/min in humans), is an early predictor of many glomerular diseases, such as various glomerulonephritides and diabetic nephropathy and is an established marker of endothelial dysfunction. It is also a feature of acute systemic inflammation or stress, such as following trauma (18), operations (6, 16), thermal injury (30), or in the systemic inflammatory response syndrome (SIRS) (4). The pathophysiological alterations resulting in microalbuminuria have only rarely been investigated. For example, it is not precisely known whether (proximal) tubular dysfunction is the major cause of microalbuminuria or whether charge- or size-selective alterations of the glomerular filtration barrier, or both, are affected. In a recent study, we found that early diabetic microalbuminuria in rats was mainly related to size-selective changes in the glomerular barrier (25) and that charge alterations were just secondary. Also, the glomerular alterations following pronounced ischemia-reperfusion (I/R) injury could be mainly ascribed to size-selective changes, although after less severe I/R challenge, charge-selective alterations were also indicated (24).

The purpose of the present study was to investigate how systemic inflammation induced by bacterial lipopolysaccharide (LPS) affects the glomerular filtration barrier and to compare these changes with those occurring in acute anaphylaxis. It should be noted that not only cells of the innate immune system, but also podocytes (5), have LPS receptors, such as toll-like receptor-4 (TLR-4) and CD14 (2). Exposure of mammals to relatively small quantities of LPS leads to an acute inflammatory response, mediated in part by the release of proinflammatory cytokines, such as interleukin (IL)-1, IL-6, and tumor necrosis factor (TNF)-α. SIRS, such as induced by LPS, involves vasodilatation and increases in vascular permeability, leading to an increased vascular leakage of macromolecules in many organs. The renal responses to early septicemia with respect to tubular function, changes in glomerular filtration rate (GFR), and in renal blood flow, particularly that in the renal medulla, have been thoroughly investigated earlier (17). However, the effects of systemic inflammation on glomerular permselectivity in vivo have not been assessed in depth. Even though SIRS, or postoperative or posttraumatic conditions (16, 18), often leads to microalbuminuria, it is actually not known to what extent the increased urinary albumin excretion rate may just be due to a tubular defect, or really reflects an increased glomerular permeability.

Dextran causes anaphylaxis in rats by inducing degranulation of mast cells, with massive release of serotonin (5-HT) and histamine, a marked fall in mean arterial blood pressure (MAP), and peripheral edema (19, 31). Both 5-HT and histamine cause vascular protein leakage via gaps that form between endothelial cells, mostly in postcapillary venules (11, 15). These changes are transient and occur within 10–15 min. In this study, we wanted to study whether such rapid alterations also occur within the glomerular filtration barrier and to compare such glomerular permeability changes with those occurring in endotoxemia-induced systemic inflammation. To study the functional glomerular alterations occurring in early septicemia and in anaphylactic shock in rats, we inves-
tigated the urine excretion of infused fluorescein isothiocyanate (FITC)-Ficoll (70/400), a neutral, polydisperse polysaccharide that is not reabsorbed by the proximal tubules, allowing the assessment of glomerular permeability by the simultaneous measurement of fractional glomerular clearances (θ; sieving coefficients) of a broad spectrum of molecular sizes. The experiments were specially designed so as to detect changes in the sieving pattern of Ficolls of high molecular weight (MW < 400,000). Furthermore, using a tissue uptake technique, we also assessed the θ for native (negatively charged) 125I-labeled human serum albumin (RISA). Although we noted rapid, transient, and reversible changes in glomerular permeability to Ficoll after dextran-induced anaphylaxis, increases in glomerular permeability during endotoxemia-induced inflammation occurred first after 2 h of LPS exposure.

MATERIALS AND METHODS

Animals. Experiments were performed in 46 male Wistar rats (Möllegård, Lille Stensved, Denmark) with an average body weight of 279.5 ± 6.3 g. The rats were kept on standard chow and had free access to water until the day of the experiment. The animal Ethics Committee at Lund University approved the animal experiments.

Surgery. The rats were anesthetized with an intraperitoneal injection of pentobarbital sodium, 60 mg/kg, and animals were placed on a thermostatically controlled heating pad to keep body temperature at 37°C. A tracheotomy was performed to facilitate breathing. The tail artery was cannulated (PE-50 cannula) for blood pressure monitoring and registration of heart rate (HR) on a polygraph (model 7B; Grass Instruments, QuinCY, MA) and for repeated injections of maintenance anesthesia (pentobarbital sodium). The left carotid artery and the left and right external jugular veins were cannulated (PE-50 cannula) for blood sampling and infusion purposes, respectively. After a small flank incision, the left ureter was cannulated (PE-10 cannula) for urine sampling, and the incision was sealed with Histoacryl (Melsungen, Germany).

Experimental procedures. Depending on exposure schedule and time to glomerular sieving measurements, rats were divided into four experimental groups and two sham groups described below. Drug (or saline) infusion started after an initial resting period (20 min), during which a control GFR measurement was performed.

Endotoxemia. Endotoxemia was induced by an intravenous bolus dose of 3 mg/kg of LPS (Escherichia coli 0111:B4; Sigma, St. Louis, MO), followed by a constant intravenous infusion of 6 mg/kg LPS for 30 min. To find out the response time to LPS, measurements were continued for an additional 60 min in one group of rats, in which Ficoll sieving measurements were performed at 60 and 90 min after endotoxemia (ENDO-60/90; n = 7) after start of the infusion, or for 120 min in another group (ENDO-120; n = 7). For the last 33 min in the ENDO-120 group and the last 63 min in the ENDO-60/90 group, FITC-Ficoll (70/400) was infused intravenously, of which the first 20 min (in the ENDO-60 and ENDO-120 groups) or 50 min (in the ENDO-90 group) served as a “Ficoll saturation period” and the following 5 min as a period of glomerular Ficoll sieving assessment. RISA was given intravenously for the last 8 min of the experiment, as described below.

Anaphylaxis. Rats immediately develop anaphylaxis in response to dextran (31). Thus, to induce anaphylaxis, Dextran-70, 250 μl Macrodex (60 mg/kg; Meda, Solna, Sweden), was given intravenously as a bolus. It was possible to obtain urine and to measure Ficoll sieving and GFR during the first 5 min following dextran administration (ANA-5; n = 9). But after 10 min urinary flow was markedly reduced. In this group, FITC-Ficoll (70/400) was infused (for equilibration) for 25 min before the dextran challenge, with a Ficoll measurement period starting at 2 min after the dextran bolus and ending at 7–8 min after the bolus. In a second group of rats followed for 40 min after the dextran injection, we noted a large fall in urine flow and MAP after ~10 min following the dextran challenge, and, because of that, 200 μl of horse serum (SVA, Uppsala, Sweden) were given one time or several times to try to normalize urine flow and MAP to preanaphylactic levels. The rationale for performing this “volume resuscitation,” except for keeping the animals alive during the anaphylactic shock, was to obtain urine for measurement of GFR or θ in the time period following the hyperacute reaction to anaphylaxis. Thanks to the volume replenishment, measurements could be performed at 40 min (ANA-40; n = 9), but, because of subsequent reductions in urine flow and GFR, we were unable to follow the animals adequately for time periods essentially longer than 40 min during anaphylaxis.

Sham animals. The θ to high-MW Ficolls (mol. radius >50 Å) in sham animals in vivo in this experimental setting are extremely low and comparable to the fractional clearance of proteins of equivalent size (24, 25). Sham animals for the ENDO groups (SHAM-120; n = 7) received 120 min of constant NaCl infusion, 10 ml/kg h −1, and, matching (in time) the infusion of LPS in the ENDO groups, a sham infusion of an extra 200 μl NaCl during 30 min. Sham animals for the ANA-5 group (SHAM-5; n = 8) obtained a bolus of NaCl (250 μl) 5 min before the Ficoll sieving assessment. Because there were no indications of changes in glomerular permeability between 5 and 120 min in the sham animals in the present experiments, nor in control rats treated with FITC-Ficoll-400 (10 mg/ml) (TdB Consultancy, Uppsala, Sweden) and FITC-Ficoll-70 (10 mg/ml) (TdB Consultancy) in a 24:1 relationship, was administered as a bolus together with FITC-inulin (TdB Consultancy). The bolus dose (FITC-Ficoll-70, 40 μg; FITC-Ficoll-400, 960 μg and FITC-Inulin, 500 μg) was followed by a constant infusion of 10 ml/kg h −1 (FITC-Ficoll-70, 20 μg/ml; FITC-Ficoll-400, 0.48 mg/ml; FITC-inulin, 0.5 mg/ml; Cr-EDTA, 0.3 MBq/ml) for 20 min, after which urine was collected for a 5-min period, with a midpoint (2.5 min) plasma sample (80 μl) also collected. For animals treated with dextran, the intravenous infusion rate was increased to 15 ml/kg h −1 throughout the experiments to avoid dehydration and to try to preserve MAP in the animals. A high-performance size exclusion chromatography (HPLC) system (Waters, Milford, MA) was used to determine size and concentration of the Ficoll samples. Size exclusion was achieved using an Ultrahydrogel-500 column (Waters). The mobile phase was driven by a pump (Waters 1525), and fluorescence was detected with a fluorescence detector (Waters 2475) with an excitation wavelength at 492 nm and an emission wavelength at 518 nm. The system was controlled by Breeze Software 3.3 (Waters). The column was calibrated with Ficoll standards and protein standards described at some length in a previous paper (1). The θ of FITC-Ficoll 70/400 was determined as the fractional clearance from:

\[ \theta = \frac{C_{FP} \times C_{P}}{C_{FP} \times C_{P} + C_{DP} \times C_{D}} \] (1)

where C_{FP} represents the Ficoll urine concentration, C_{DP} represents the inulin concentration in plasma, C_{P} the Ficoll concentration in plasma, and C_{D} the inulin concentration in urine.

GFR. GFR was determined by measuring renal clearance of 51Cr-EDTA (Amersham Bioscience, Buckinghamshire, UK) and FITC-inulin. 51Cr-EDTA was given as a bolus dose at the start of the experiments (0.3 MBq in 0.2 ml iv) followed by a constant infusion of 10 ml/kg h −1 (0.3 MBq/ml) (together with NaCl) throughout the experiments. For repeated measurements of the plasma to urine 51Cr-EDTA clearance during the study, blood samples were performed approximately every 20 min using microcapillaries (10 μl). Urine was sampled every 10–30 min of the experiment. Radioactivity in blood samples and urine samples was measured in a gamma counter (Wizard 1480; LKP Wallac, Turku, Finland). Hematocrit (50 μl) was...
assessed two or three times throughout the experiment, to be able to convert blood radioactivity into plasma radioactivity.

The urinary excretion of $^{31}$Cr-EDTA (and FITC-inulin) per minute ($U_i \times V_u$) divided by the concentration of tracer in plasma ($P_i$) was used to calculate GFR according to:

$$GFR = \frac{U_i \times V_u}{P_i}, \quad (2)$$

where $U_i$ represents the tracer concentration in urine, and $V_u$ the flow of urine per minute.

**Tissue uptake technique for assessing $\theta$ for $^{125}$I-HSA.** After collection of urine and plasma for Ficoll determinations, $^{125}$I-HSA (0.2 MBq; Institute for Energy Technique, Kjeller, Norway) was administered via the tail artery as a bolus. During an 8-min period, six blood samples (25 μl) and one urine sample were collected for estimation of the sieving coefficient of $^{125}$I-HSA (RISA). Thereafter, a whole body washout was performed via the left external jugular vein (25 ml/min) for 8 min. The washout fluid mixture contained equal amounts of 0.9% saline and heparinized horse serum (SVA). After a laparotomy, the interior of the left kidney was fixed within 1 min after start of washout and cut open for collection of the rinse fluid. Following complete washout, the kidneys were removed, and the cortex was dissected out and assessed with respect to radioactivity. To reduce the influence of free $^{125}$I, urine samples were precipitated with 10% trichloroacetic acid (TCA) and spun down, and the supernatant (free $^{125}$I) was discarded. All samples were measured for radioactivity in the gamma counter mentioned above.

The sieving coefficients for RISA were calculated from the amount of tracer radioactivity accumulated in the left kidney cortex plus the TCA-precipitable urine tracer activity (collected during the tracer infusion period and amounting to a maximum of 5–10% of total cortical radioactivity) divided by the average plasma tracer concentration, by the tracer circulation time, and by GFR.

**Pore analysis.** The two-pore model (10, 22, 29) was used to analyze the $\theta$ data for Ficoll (mol. radius 15–80 Å). A nonlinear least-squares regression analysis was used to obtain the best curve fit, using scaling multipliers as described at some length previously (10).

**Statistics.** Values are expressed as means ± SE. Differences between groups were tested using nonparametric analysis of variance with the Kruskal-Wallis test and post hoc testing using the Mann Whitney U-test. Significance levels were set at $P < 0.05$. **$P < 0.01$, and ***$P < 0.001$. All statistical calculations were made using SPSS 11.0.3 for Macintosh OSX (SPSS, Chicago, IL).

### RESULTS

**MAP and HR.** The SHAM group showed a stable, or only moderately reduced, MAP during the course of the experiment (Fig. 1), and also a moderate increase in HR. By contrast, endotoxin caused a rapid (within 5 min) fall in MAP, from 130 ± 2.4 to 54.3 ± 4.6 mmHg ($P < 0.01$) in the ENDO-(60)/90 group and from 116 ± 3.9 to 53.3 ± 4.8 mmHg ($P < 0.01$) in the ENDO-120 group. After a spontaneous recovery of the MAP, which usually occurred within the next 20–30 min, there was again a slow reduction of MAP with time. Thus there appeared to be a bimodal MAP response to endotoxin. Furthermore, endotoxin caused an increased HR, from 383 ± 13.8 beats/min at the start to 447 ± 17.1 beats/min ($P < 0.05$) after 120 min, which was not seen in the 120 sham group. Similar to the LPS group, the anaphylactic group (Fig. 2) showed an initial, but less rapid, decrease in MAP. Thus, during the first 5 min after the dextran infusion, MAP was rather stable, starting at 116 ± 5.7 and being reduced to 104 ± 6.0 mmHg [not significant (NS); ANA-5 group]. In the ANA-40 group, MAP fell from 99.2 ± 3 to 47.1 ± 1.5 mmHg ($P < 0.01$) 15 min after the dextran administration. The ANA-40 group nearly recovered their MAP toward the end of the experiment, conceivably mainly because of the volume resuscitation performed (Fig. 2). There was also a slight tendency of increase in HR from 320 ± 18.1 to 332 ± 8.9 (NS). 

**GFR.** In the SHAM group, GFR showed a slightly higher value at the end of the experiments than at the start (Fig. 3), whereas, in the ENDO groups, there was a decrease in GFR, ~20 min after start of the LPS infusion, from 0.70 ± 0.05 to 0.35 ± 0.04 ml/min·1·g$^{-1}$ ($P < 0.01$) in the ENDO-(60)/90 group and from 0.73 ± 0.05 ml/min·1·g$^{-1}$ to 0.49 ± 0.09 ml/min·1·g$^{-1}$ ($P < 0.05$) in the ENDO-120 group. In the following period (at ~50 min), GFR had recovered, but then again tended to fall as part of the septic condition. In the anaphylaxis groups, GFR could not be measured during the period from 10 to 20 min after the dextran bolus because of the marked reduction in urine flow. However, early in the experiment (0–10 min), urine flow and GFR were remarkably well preserved (Fig. 4) in the ANA-5 and ANA-40 group. By the end of the experiments (at 40 min), conceivably thanks to the volume resuscitation, GFR seemed to have partly recovered vs. preanaphylactic value(s) in the ANA-40 group (0.65 ± 0.06 vs. 0.72 ± 0.04 ml/min·1·g$^{-1}$; NS).

**$\theta$ for FITC-Ficoll.** Figure 5 demonstrates the sieving coefficient ($\theta$) vs. Stokes-Einstein radius ($a_e$) curves for Ficoll molecules ranging in radius from 15 to 80 Å for the ENDO-120 group vs. the SHAM-120 group. In the $a_e$ range between 55 and 80 Å, the ENDO-120 group showed a clearly increased $\theta$ compared with SHAM ($P < 0.001$). This increased permeability to high-mol. Ficolls was, however, not seen for either the ENDO-60 or the ENDO-90 measurements, as shown in Fig. 6, demonstrating a time dependency of the changes in glomerular permeability following endotoxin.

In the acute anaphylaxis (ANA-5) group, there were significantly higher sieving coefficients for Ficoll 55–80 Å ($P < 0.001$) than in the SHAM-5 group (Fig. 7). By contrast, there was no significant difference between the ANA-40 group and either of the SHAM groups.

**Two-pore modeling.** The best curve fits of $\theta$ vs. $a_e$ for Ficoll according to the two-pore model were obtained using the parameters listed in Table 1 (ENDO groups) and Table 2 (ANA groups).
The fractional ultrafiltration coefficient accounted for by large pores, mainly reflecting the number of large pores, and the fractional fluid flow through large pores were more than doubled in the ENDO-120 group and the acute anaphylactic (ANA-5) group, but remained unchanged vs. control in ENDO-(60)/90 groups and in the ANA-40 group. In acute anaphylaxis, not only the large pore number, but also the large pore radius, was acutely increased (188 ± 10.1 vs. 115 ± 3.0; \( P = 0.01 \)). The effective area over unit diffusion path length seems to have been reduced in the ANA-5 group.

**Discussion**

This is, to our knowledge, the first detailed in vivo study of the alterations in the glomerular permeability that occur during systemic inflammation induced by endotoxemia and in anaphylactic shock. The major result of the study is that early endotoxemia-induced systemic inflammation and anaphylactic shock both reduce the size-selectivity of the glomerular filtration barrier by increasing the number of large pores in the glomerular filter, rather than affecting the glomerular charge-selectivity. Acute anaphylaxis caused a rapid, transient change in glomerular permeability, completely reversible within 40
min, whereas LPS induced an increase in the θ to large Ficoll molecules, which was manifest only after 2 h. These two completely different response patterns apparently reflect two different mechanisms of action of the mediators involved in endotoxin-induced shock and in anaphylactic shock.

It is well accepted that LPS administration leads to activation of TLR4 on cells in the innate immune system (2). TLR4 is present on monocytes and other cell types, including podocytes, and mediates a series of inflammatory events. Exposure to endotoxin thus initiates a complex cascade, involving various proinflammatory and anti-inflammatory cytokines, such as IL-6, TNF-α, IL-10, and IL-18, activating white cells and other inflammatory response mediators, including adhesion molecules, complement factors, oxygen-derived free radicals, and procoagulant factors. Especially, TNF-α is considered a crucial mediator of both acute and chronic inflammatory responses, including microalbuminuria (9). The slow and gradual change in glomerular permeability in response to endotoxin thus seems to reflect the gradual activation of multiple and integrated inflammatory response systems over time.

Perhaps the most startling finding of the present study was the immediate and prominent increase in glomerular permeability in anaphylaxis, a response completely reversible within 40 min. In rats, dextran induces anaphylaxis by causing degranulation of mast cells, with massive release of 5-HT and histamine. In turn, these biogenic amines cause precapillary vasodilation (histamine) and/or postcapillary vasoconstriction (5-HT), raising capillary pressure, and an increased microvascular leakage of proteins (12, 22). This leakage occurs via gaps that transiently form between endothelial cells, mostly in postcapillary venules (11, 19). Despite the fall in MAP, there was thus a marked, transient increase in glomerular permeability occurring in parallel with an increased transvascular leakage of RISA in skin, lung, and muscle (presented in a subsequent study) in anaphylaxis.

Overall, it should be noted, however, that the glomerular barrier apparently is rather unresponsive to 5-HT and histamine following the immediate insult, because glomerular permeability was completely restored within 40 min. This is actually in line with previous studies using dextran molecules (18–44 Å in radius) as markers of glomerular permselectivity (8) or using a technique for assessing vascular labeling of endothelial gaps with carbon (27). The mentioned studies thus failed to demonstrate any renal permeability effects of histamine or 5-HT, except for showing some occasional leaky sites in peritubular junctions.
In conclusion, the present study, specially designed to assess glomerular sieving coefficients for high-molecular-weight Ficoll molecules, demonstrated an early, transient increase in glomerular permeability to Ficoll in anaphylactic shock, completely reversible within 40 min. By contrast, endotoxemia increased glomerular permeability first after 2 h. In both endotoxemic and anaphylactic shock, the increased glomerular permeability appeared to occur by an increase in the number of large pores in the glomerular filter, rather than affecting the glomerular charge selectivity.

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Loss of size selectivity of the glomerular filtration barrier in rats following laparotomy and muscle trauma

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Axellsson J, Mahmutovic I, Rippe A, Rippe B. Loss of size selectivity of the glomerular filtration barrier in rats following laparotomy and muscle trauma. Am J Physiol Renal Physiol 297:F577–F582, 2009. First published July 8, 2009; doi:10.1152/ajprenal.00246.2009.—Posttraumatic microalbuminuria may be caused by either charge- or size-selective alterations in the glomerular filtration barrier, or both, and/or to a reduction in proximal tubular protein reabsorption. This study was performed to elucidate the pathophysiology of the increases in glomerular permeability occurring in rats exposed to a laparotomy or to a laparotomy and muscle trauma. In anesthetized Wistar rats (250–280 g), the left ureter was cannulated for urine collection, while simultaneously blood access was achieved. Rats were exposed to trauma by a laparotomy (L; n = 8), or by a combination of L and muscle trauma (MT; L + MT) induced by topical blunt injury of the abdominal muscles bilaterally. After L, muscles were crushed using hemostatic forceps at either 2 × 2 sites (“small” MT; n = 9), or at 2 × 5 sites (“large” MT; n = 9). Sham groups (n = 16), not exposed to a laparotomy, were used as controls. The glomerular sieving coefficients (θ) to polydisperse FITC-Ficoll-70/400 (molecular radius 13–80 Å) were determined at 5 or 60 min after L and L + MT, respectively, from plasma and urine samples, and analyzed by high-performance size-exclusion chromatography. A tissue-uptake technique was used to assess θ for 125I-labeled serum albumin. L, with or without MT, increased θ for Ficoll55–80Å and albumin rapidly and markedly. θ-Ficoll55–80Å thus increased approximately threefold, and θ for albumin significantly, for all trauma groups. According to the “two-pore model” of glomerular permeability, these changes mainly reflect an increase in the number of large pores in the glomerular filter without any primary changes in the charge-selective properties of the filter.

microalbuminuria: glomerular sieving coefficients; albumin; Ficoll; capillary permeability

MICROALBUMINURIA, i.e., just moderately elevated rates of albumin excretion in the urine (20–200 µg albumin/min), is an established marker of endothelial dysfunction and occurs in vascular disease (9) and diabetic nephropathy, but also after surgery (6, 13), body trauma (15), and in fever, sepsis (3), etc. The exact pathophysiology of microalbuminuria is not known. Is it primarily due to tubular dysfunction, resulting in a reduced proximal tubular reabsorption (PTR) of albumin, or is it due to alterations of the charge- or size-selective properties of the glomerular filtration barrier, or both? Earlier studies on glomerular Ficoll sieving in intact rats indicate that ischemia-reperfusion (I/R) injury (18), early diabetic nephropathy (19), or sepsis (LPS infusion) (3) produces increases in glomerular permeability based on reductions in the size selectivity, of the barrier with only secondary changes in charge selectivity. Various kinds of significant trauma or inflammation may elicit a systemic inflammatory response syndrome (SIRS) (5). Such an inflammatory response involves the activation of multiple pathways, including the coagulation and complement cascades, as well as activation of monocytes, lymphocytes, and other inflammatory cells to release chemokines, cytokines, and reactive oxygen species (ROS) and other proinflammatory (and anti-inflammatory) agents. Interactions of such agents and/or activated cells with the glomerular filtration barrier are thought to result in microalbuminuria. Moderate trauma, such as after hip and knee surgery, thus results in low-grade microalbuminuria, being most prominent during the first day after surgery (13). Since both the urinary albumin/creatinine and IgG/creatinine ratios increased in parallel, and since tubular markers were not seen to peak in the urine until the second day after an operation, it was concluded that posttraumatic proteinuria may be due to a size-selective defect in the filter, and not primarily due to reductions in PTR. In fact, also after burns, there was a biphasic proteinuria response, with an initial microproteinuria resolving within 24 h, reflecting a size-selectivity defect, and with a second protein excretion phase, peaking 3–5 days postinjury, with a pattern signaling tubular proteinuria (22).

In a recent study (3), we found that acute dextran-induced anaphylaxis in rats caused a rapid, transient increase in glomerular permeability, completely reversible within 40 min, whereas after infusion of lipopolysaccharide (LPS), producing sepsis, a more gradual permeability response, evident first after 120 min, was seen. These two different response patterns apparently reflect two different patterns of action of the mediators involved in SIRS. In acute anaphylaxis, the immediate release of histamine (from mast cells) and other proinflammatory agents seemed to have caused an initial glomerular permeability increase, whereas the permeability alterations occurring during endotoxemia appeared to follow upon a more gradual activation of proinflammatory mechanisms.

That the glomerular barrier can reversibly increase its permeability within minutes may seem remarkable. In the present study, we address the question of whether glomerular selectivity can be promptly reduced also upon surgery and/or muscle trauma. Hence, we investigated the functional behavior of the glomerular filtration barrier in response to a laparotomy, with and without skin dissection, and with and without graded muscle trauma in rats. Glomerular size and charge selectivity were assessed in vivo using two different techniques. First, we
used FITC-Ficoll 70/400, a neutral polysaccharide which is not reabsorbed by the proximal tubules, to assess the glomerular permeability (θ; sieving coefficients) for a broad spectrum of molecular sizes, emphasizing the glomerular sieving pattern of Ficoll molecules of high molecular weight (MW ~ 400,000). Second, by using a tissue-uptake technique, we were also able to assess the θ for 125I-labeled native (negatively charged) human serum albumin (HSA).

**MATERIALS AND METHODS**

*Animals and general surgery.* Experiments were performed in 67 male Wistar rats (Möllegård, Lille Stensved, Denmark) with an average body weight of 273 ± 4.1 g. The rats had free access to standard food and water until the day of the experiment. The animal Ethics Committee at Lund University approved the animal experiments. Anesthesia was induced by an intraperitoneal injection of pentobarbital sodium (60 mg/kg body wt) and maintained through repeated intra-arterial injections of the same drug. The rats were placed on a heating pad to maintain body temperature at 37°C. The tail artery was cannulated (PE-50 cannula) for continuous monitoring of blood pressure and heart rate registration on a polygraph (model 7B, Grass Instruments, Quincy, MA), and for administration of anesthesia. A tracheotomy was performed to facilitate breathing. The left carotid artery and left jugular vein were cannulated (PE-50) for blood sampling and infusions, respectively. Following an intravenous bolus dose of furosemide (1.5 mg/kg body wt, Furosemid, Recip AB, Arsta, Sweden) to induce diuresis, and after a small abdominal incision (~10 mm), the left ureter was exposed and cannulated (PE-10 connected to a PE-50 cannula) for urine sampling. The dead space of the cannula was 7–8 μL, and the diuresis after furosemide (20–40 μL/min), although somewhat declining over time, essentially remained elevated throughout the experiment (1.5 h).

*Experimental protocol.* After an initial resting period of 10–15 min following the cannulation of the left ureter, trauma of different types was induced. The primary trauma induced, after the small abdominal incision needed for the ureter cannulation, was a ~50-mm-long laparotomy (L) along the abdominal midline and along the linea alba of the abdominal muscle wall. This was the only trauma induced in two groups, followed for either 5 or 60 min, denoted L5 (n = 9) and L60 (n = 8), respectively. In one additional L group, the skin was dissected (D) away from musculus rectus abdominis following the L, bilaterally (~25 mm), at each side of the incision, and investigated at 60 min, and denoted the L60 (n = 8). In three additional groups, crush injury was inflicted upon the abdominal muscles after L and D, by topically “pinching” (crushing) the m. rectus abdominis bilaterally using a pair of hemostatic forceps according to Bansch et al. (4) following additional intravenous analgesia in the form of phentylamine (0.04 mg/kg body wt, Pharmalink). Muscle crush trauma (MT) was induced by either 2 × 2 or 2 × 5 pinches, the former group denoted LD-MTsmall and followed for 60 min (i.e., LD-MTsmall-60; n = 8), and the latter denoted LD-MTlarge, and followed for either 5 (LD-MTlarge-5; n = 9) or 60 min (LD-MTlarge-60; n = 9). The trauma force was standardized by closing the forceps for about 10 s three times at every location. Each “pinch” caused a muscle crush injury at a right angle from the free edge of the muscle incision of the L, either at two or at five locations on each side of the L, and each being ~3 mm × 35 mm in size. The L incision was then closed by small clips. θ for Ficoll was thus measured at 60 min after the trauma induction, except in two “acute” groups, L and LD-MT-5, where θ was measured already 5 min posttrauma. For sham animals, no L was done and θ for Ficoll was measured at 5 or 60 min after the initial control period (SHAM5; n = 8 and SHAM60; n = 8, respectively).

*Sieving of FITC-Ficoll.* Ficoll 70 (10 mg/ml) and Ficoll 400 (10 mg/ml) labeled with FITC were obtained from TdB Consultancy (Uppsala, Sweden). A mixture containing FITC-Ficoll 400 (0.96 mg), FITC-Ficoll 70 (40 μg), FITC-labeled inulin (0.5 mg, TdB Consultancy) was given as a priming bolus dose followed by a constant infusion (12 ml·kg⁻¹·h⁻¹) of FITC-Ficoll 400 (0.36 mg/ml), FITC-Ficoll 70 (15 μg/ml), FITC-inulin (0.375 mg/ml), and 51Cr-EDTA (0.225 MBq/ml) for a minimum of 20 min, after which urine was collected for a 5-min period, with a midpoint (2.5 min) plasma sample collected.

*HPLC system.* (Waters, Milford, MA) was used to determine size and concentration of the Ficoll samples. Size exclusion was achieved using an Ultrahydrogel-500 column (Waters). The mobile phase was driven by a pump (Waters 1525) and fluorescence was detected with a fluorescence detector (Waters 2475) with an excitation wavelength at 492 nm and an emission wavelength at 518 nm. The samples were loaded to the system with an autosampler (Waters 717 plus), and the system was controlled by Breeze Software 3.3 (Waters). The column was calibrated with Ficoll and protein standards described in a previous paper (1).

θ of FITC-Ficoll 70/400 were determined as the fractional clearance from θ = (Ctest-Cref)/(Ctest-Cref), where Ctest represents the Ficoll urine concentration, Cref represents the inulin concentration in plasma, Ctest the Ficoll concentration in plasma, and Cref the inulin concentration in urine.

*Glomerular filtration rate.* The glomerular filtration rate (GFR) was assessed as the renal clearance of 51Cr-EDTA (Amersham, Bioscience, Buckinghamshire, UK) and was measured repeatedly throughout the experiment. During the FITC-Ficoll sieving period, GFR was also assessed from the urine clearance of FITC-inulin. 51Cr-EDTA was given as a bolus dose at the start of the experiments (0.3 MBq in 0.2 ml intravenously) followed by a constant infusion 12 ml·kg⁻¹·h⁻¹ (0.225 MBq/ml; together with NaCl) throughout the experiment. For the animals followed for 60 min, GFR was measured during a period of 5–10 min before the trauma induction and then at 30 and 60 min posttrauma and also during the FITC-Ficoll-sampling period (5 min). Blood sampling, using microcapillaries (10 μl), was performed every 10 min of the experiment, and urine was thus sampled every 30 min of the experiment except in the animals that were followed for only 5 min. Radioactivity in blood and urine samples was measured using a gamma counter (Wizard 1480, LKP Wallac, Turku, Finland). Hematocrit was assessed throughout the experiments so as to convert blood radioactivity into plasma radioactivity. The urinary excretion of 51Cr-EDTA (and FITC-inulin) per minute (Ut×Vu) divided by the concentration of tracer in plasma (P), was used to calculate GFR, where Ut represents the tracer concentration in urine and Vu the flow of urine per minute.

*Tissue-uptake technique for assessing θ for 125I-HSA.* At the end of each experiment, albumin θ was measured using a tissue-uptake technique. 125I-HSA (0.2 MBq; Institute for Energy Technique, Kjeller, Norway) was administered via the tail artery as a bolus, after Ficoll urine sampling was completed. Six blood samples (25 μl) and one urine sample were collected during 8 min for estimation of the θ for 125I-HSA. Thereafter, a whole body washout was performed via the left external jugular vein (25 ml/min) for 8 min. The washout fluid mixture contained equal amounts of 0.9% saline and heparinized horse serum (SVA, Uppsala, Sweden). The inferior vena cava was freed and cut open for collection of rinse fluid. The kidneys were then removed, and the cortex was dissected and assessed with respect to radioactivity in a gamma counter. To reduce the influence of free 125I, urine samples were precipitated with 10% TCA, centrifuged, and the supernatant (free 125I) was discarded. For the tissue-uptake technique, renal tracer protein 125I-HSA clearance was calculated from the amount of tracer radioactivity accumulated in the left kidney cortex plus the TCA-precipitable urine tracer activity divided by the average plasma tracer concentration, by the tracer circulation time, and by GFR.

*Pore analysis.* The two-pore model (10, 16, 20) was used to analyze the θ data for Ficoll (molecular radius ~13–80 Å). A nonlinear
least squares regression analysis was used to obtain the best curve fit, using scaling multipliers as described at some length previously (10).

Statistical analysis. Values are presented as means ± SE. Differences among groups were tested using nonparametric analysis of variance with the Kruskal-Wallis test and post hoc tested using the Mann-Whitney U-test. Bonferroni corrections for multiple comparisons were made. Significance levels were set at P < 0.05, P < 0.01, and P < 0.001. All statistical calculations were made using SPSS 11.0.3 for Macintosh OSX (SPSS, Chicago, IL).

RESULTS

Mean arterial pressure and heart rate. The sham groups (SHAM5 and SHAM60) and the two short experimental groups, L5 and LD-MTlarge-5, showed a stable mean arterial pressure (MAP) and heart rate (HR) during the course of the experiment. The L60, LD60, and LD-MTsmall-60 groups showed a minor increment in MAP and HR, peaking at 15 min after the trauma induction. In the LD-MTsmall-60 group, MAP thus increased from 90.6 ± 4.4 to 109.4 ± 4.4 mmHg (P < 0.05), and HR increased from 359 ± 13 to 399 ± 6 beats/min (P < 0.05) at 15 min after the trauma. The LD-MTlarge-60, however, showed a more stable MAP and HR following the trauma. All changes tended to be reversed to near starting values by the end of the experiment.

GFR. GFR remained more or less stable in all sham and experimental groups, with the exception of the LD-MTlarge-60 group and the LD60 group, where it decreased from 0.70 ± 0.05 to 0.48 ± 0.04 ml/min·100 g−1 (P < 0.01) and from 0.67 ± 0.05 to 0.52 ± 0.06 ml/min·100 g−1 (P < 0.05), respectively, at 15 min, and in the L60 group, where GFR increased from 0.61 ± 0.08 to 0.75 ± 0.03 ml/min·100 g−1 (P < 0.05) at 15 min after the trauma induction (Fig. 1, A and B). Again, at the end of the experiments, the observed changes were more or less reversed.

Glomerular θ for FITC-Ficoll vs. Stokes-Einstein radius. Figure 2A shows the glomerular Ficoll θ vs. molecular radius [Stokes-Einstein radius (aε)] for the experimental groups exposed to L alone, i.e., in L5 and L60, respectively. There was a significant increase in the θ for Ficoll55–80Å compared with sham groups already at 5 min, the increase being largely sustained at 60 min. For Ficoll79Å, θ increased from 2.37 × 10−5 ± 5.80 × 10−6 (in SHAM5) to 1.71 × 10−4 ± 4.39 × 10−5 in L5 and from 3.32 × 10−5 ± 1.38 × 10−5 (in SHAM60) to 1.22 × 10−4 ± 2.88 × 10−5 in L60, respectively. Adding skin dissection (D) and/or moderate-to-large muscle crush trauma (MT) to the L did not further increase the θ in the aε range of 55–80 Å (Fig. 2B). For Ficoll103Å, this increase in θ was from 2.37 × 10−5 ± 5.80 × 10−6 (in SHAM5) to 2.5 × 10−4 ± 6.1 × 10−5 in LD-MTlarge-5 and from 3.32 × 10−5 ± 1.38 × 10−5 (in SHAM60) to 1.3 × 10−3 ± 2.34 × 10−4 in LD-MTlarge-60, respectively. Again, there was a rapid and sustained increase in θ for high-molecular-weight Ficolls, with no graded response relative to the magnitude of the trauma induced. Data derived from Ficoll sieving curves for the experimental groups not shown in Fig. 2, A and B, are shown in Tables 1 and 2. The two sham groups showed (near) identical glomerular Ficoll sieving curves.

Two-pore modeling. The parameters generated from the best fit of the measured Ficoll sieving curves to the two-pore model are shown in Tables 1 and 2. Data demonstrate that the fractional hydraulic conductance accounted for by the large pores (aL) had increased at least twofold in all of the experimental groups compared with the sham groups, indicating the formation of an increased fraction of large pores in the glomerular filter induced by the laparotomy and/or muscle trauma. The fractional fluid flow through large pores/GFR ratio was more than doubled in all of the groups compared with sham rats. In L5 and LD-MTlarge-5, not only the large pore number but also the large pore radius acutely increased compared with SHAM5. Furthermore, the effective diffusion area over diffusion path length (aε/ΔX) was reduced in both of these groups.

Glomerular θ for albumin. Figure 3A demonstrates an acutely significant increase in θ for albumin in L5 and LD-MTlarge-5 vs. SHAM5 (5.85 × 10−4 ± 2.56 × 10−5 and 5.02 × 10−4 ± 0.07 × 10−5 vs. 3.56 × 10−4 ± 0.08 × 10−5), respectively. Figure 3B shows θ for albumin in experiments continued for 60
caused no further significant increases in glomerular permeability.

Major body trauma or systemic inflammation may result in excessive inflammatory response patterns, leading to an increased microvascular permeability in the form of increases in the transcapillary escape rate of albumin and microalbuminuria, and in severe cases, acute respiratory distress syndrome (7, 15). This response is mediated in part by activation of monocytes and other inflammatory cells and by the release of proinflammatory cytokines, such as interleukin (IL)-1 and IL-6. Activated leukocytes adhere to the endothelium and may cause additional local, reversible increases in capillary permeability, or endothelial damage, by releasing permeability-increasing agents and/or reactive oxygen species. Furthermore, hemodynamic alterations occur, in this study being most evident directly after the trauma induction (see below). The present study emphasizes the rapidity by which glomerular permeability can increase after trauma. Indeed, we found large increases in glomerular permeability already ~5 min after the trauma induction. Although the response showed a tendency to “fade” over time, it was still largely sustained at 60 min, conceivably reflecting a continual release of proinflammatory mediators initiated by the trauma induction. This is in stark contrast to the glomerular permeability response in anaphylactic shock (3), which was also very pronounced after 5 min, but which was completely reversible within 40 min. These different response patterns conceivably reflect two different types of inflammatory stimulation. In anaphylaxis, there is a rapid degranulation of mast cells with release of histamine and other mediators to the circulation, which results in very prompt and dramatic initial vascular permeability changes. In posttraumatic conditions (and in sepsis), there is obviously a more continual activation of proinflammatory mechanisms, causing more sustained responses, even though in LPS-induced sepsis, the onset of these changes was relatively slow (3).

Immediately posttrauma (in the L5 and LD-MTlarge5 groups), there was a reduction in $A_s/\Delta X$, indicating an altered glomerular hemodynamic situation. Conceivably, following trauma, similar to the situation in acute anaphylaxis, there is an acute renal vasoconstriction, mainly affecting the efferent arteriole, preventing large reductions in GFR, but reducing renal blood flow, and hence, $A_s/\Delta X$. Theoretically, if $A_s/\Delta X$ is reduced considerably more than GFR, then there will be a reduction in $\theta_s$ for Ficoll55–80Å and a tendency of an increase in $\theta_s$ for Ficoll55–80Å (17). Although slight, a depression of the

![Diagram](image-url)

**Table 1. Two-Pore Parameters Measured 5 Min After Trauma in L5 and LD-MTlarge−5 Groups vs. SHAM60 Group**

<table>
<thead>
<tr>
<th>Two-Pore Parameters</th>
<th>SHAM60 (n = 8)</th>
<th>L5 (n = 9)</th>
<th>LD-MTlarge−5 (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-pore radius ($r_s$, Å)</td>
<td>4.06 ± 0.05</td>
<td>47.0 ± 0.16</td>
<td>47.2 ± 0.16</td>
</tr>
<tr>
<td>Large-pore radius ($r_L$, Å)</td>
<td>114.6 ± 2.95</td>
<td>172.6 ± 6.60</td>
<td>164.1 ± 11.91</td>
</tr>
<tr>
<td>$a_s \times 10^7$</td>
<td>3.90 ± 0.83</td>
<td>8.67 ± 1.82</td>
<td>10.24 ± 2.19</td>
</tr>
<tr>
<td>$J_v/GFR \times 10^5$</td>
<td>10.1 ± 2.21</td>
<td>29.3 ± 6.34</td>
<td>41.2 ± 8.03</td>
</tr>
<tr>
<td>$A_s/\Delta X$, cm/g × 10−5</td>
<td>6.82 ± 0.75</td>
<td>1.77 ± 0.11</td>
<td>1.24 ± 0.20</td>
</tr>
</tbody>
</table>

Values are given as SE; n = no. of rats. See text for definitions of groups. $a_s$, fractional ultrafiltration coefficient accounted for by large pores; $J_v/GFR$, fractional fluid flow through large pores; GFR, glomerular filtration rate; $A_s/\Delta X$, effective area of unit diffusion path length. Statistical difference between SHAM and experimental groups (L5 and LD-MTlarge−5): *P < 0.05, **P < 0.01.

**Fig. 2. A:** glomerular sieving coefficients ($\theta$) vs. Stokes-Einstein radius ($a_s$) for Ficoll in the left kidney for groups subjected to laparotomy alone and observed for either 5 min (L5) or 60 min (L60). There was a rapid increment in $\theta$ for Ficoll55–80Å, which was more or less sustained over 60 min. **B:** glomerular $\theta$ vs. $a_s$ for Ficoll in the left kidney for animals exposed to laparotomy, skin dissection, and large muscle trauma observed for either 5 min (LD-MTlarge-5) or 60 min (LD-MTlarge-60). There was a rapid and large increase in $\theta$ for Ficoll55–80Å already at 5 min, being sustained at 60 min. Similar results were obtained for rats exposed to skin dissection (LD60) and moderate muscle trauma (LD-MTmed-60) (not shown).

**DISCUSSION**

Laparotomy, with or without skin dissection, and with or without ensuing muscle trauma, caused a rapid and sustained increase in $\theta$ for large Ficoll molecules and for albumin. According to the two-pore model of glomerular permeability, these changes reflect an increase in the number, and, to some extent, the radius, of the large pores in the glomerular filter with only secondary changes in its charge-selective properties. Hence, L alone was sufficient to produce prompt and marked alterations of the glomerular filtration barrier, while adding further trauma by skin dissection and blunt muscle injury
sive curve for Ficoll20–40Å can be seen in Fig. 2A. Due to the increase in glomerular permeability, θs for Ficoll55–80Å increased acutely. A further increment in θs for high-molecular-weight Ficolls can be expected to occur for hemodynamic reasons (reduction in GFR). Since, however, θs for Ficoll55–80Å 5 min after the trauma were actually not significantly different from those measured at 60 min posttrauma, when MAP and GFR had been more or less normalized, we consider the hemodynamic effects on the Ficoll sieving curves to be rather moderate.

Much to our surprise, the glomerular permeability increases in this study occurred more or less in an “all-or-none” fashion. Thus L alone caused very marked and rapid increases in glomerular permeability. No significant further increments in glomerular permeability occurred for additional trauma, in the form of skin dissection or graded muscle injury, despite the fact that very large increases in glomerular permeability have been noted in this model in puromycin aminonucleoside-induced glomerulopathy (2). Evidently, L alone seems to lead to an acute, nearly full-fledged, inflammatory response, at least with respect to the alterations causing an increased glomerular permeability. Indeed, when glomerular Ficoll sieving curves in sham (control) animals in the present study were compared together with those in a previous study (3), in which L was not done to access the left ureter, with experiments in which L had been performed (1, 17, 18), there is a much higher glomerular permeability to Ficoll55–80Å in the latter experiments. Thus, already from these data, it seems evident that L represents a major trauma, inducing sustained increases in glomerular permeability. Indeed, animals not exposed to L show very low θ for Ficoll55–80Å, being of the same order of magnitude as θ for proteins of equivalent chromatographic radii in patients lacking PTR (Dent’s disease) (14). It has thus previously been shown that the “hyperpermeability” of Ficoll55–80Å (relative to proteins having equivalent chromatographic radii) manifested across the small pores of the glomerular filter is not manifested for Ficoll55–80Å in large pores of the filter (21). This is conceivably owing to the lower ratio of θ to pore radius (<0.7) in the large pores than in small pores, so that Ficoll hyperpermeability is not manifested, (17, 18, 21).

While the Ficoll molecules in this study are largely uncharged, albumin is negatively charged at a physiological pH. According to the two-pore model of glomerular transport, negatively charged albumin (θe = 36 Å), unlike Ficoll36Å, is more or less totally confined to the large pores for its transport across the negatively charged glomerular filtration barrier, similar to Ficoll55–80Å. Thus, according to the Debye-Hückel theory of ion-ion interactions (16), negative albumin dissolved in physiological saline (or plasma) and interacting with negatively charged surfaces (e.g., pore walls), would behave similarly to a neutral molecule of radius (36 + 8) Å = 44 Å, where 8 Å is the so-called Debye length, whereas a negatively charged cylindrical small pore, having a radius of 47 Å, as in this study, interacting with a negatively charged molecule would have an effective pore radius of (47 – 8) Å = 39 Å. Thus, because negative albumin (effective radius 44 Å) is excluded from the negatively charged small pores (effective radius 39 Å), but is permeable across large pores (radius >110 Å), one would expect θs for Ficoll55–80Å and that for albumin to change more or less in parallel for purely size-selective changes in the glomerular permeability.

Table 2. Two-pore parameters in L60, LD60, LD-MTsmall–60, and the LD-MTlarge–60 groups vs. SHAM60 group

<table>
<thead>
<tr>
<th>Two-Pore Parameters</th>
<th>SHAM60 (n = 5)</th>
<th>L60 (n = 8)</th>
<th>LD60 (n = 9)</th>
<th>LD-MTsmall–60 (n = 8)</th>
<th>LD-MTlarge–60 (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-pore radius (r1), Å</td>
<td>47.3 ±0.08</td>
<td>46.7 ±0.14</td>
<td>47.1 ±0.17</td>
<td>47.3 ±0.10</td>
<td>47.4 ±0.22</td>
</tr>
<tr>
<td>Large-pore radius (r2), Å</td>
<td>136.5 ±9.5</td>
<td>124.2 ±9.88*</td>
<td>163.1 ±9.74</td>
<td>157.5 ±3.35</td>
<td>167.6 ±4.72*</td>
</tr>
<tr>
<td>αL × 10^3</td>
<td>2.98 ±0.77</td>
<td>6.0 ±1.11</td>
<td>6.16 ±1.8</td>
<td>6.83 ±1.32*</td>
<td>7.05 ±0.91*</td>
</tr>
<tr>
<td>J0L × GFR × 10^3</td>
<td>9.09 ±2.6</td>
<td>20.0 ±3.9</td>
<td>20.1 ±6.29</td>
<td>21.7 ±4.36*</td>
<td>23.4 ±3.30*</td>
</tr>
<tr>
<td>A(air) cm^2 g^-1 × 10^-5</td>
<td>1.84 ±0.14</td>
<td>1.29 ±0.21</td>
<td>2.09 ±0.20</td>
<td>1.26 ±0.09</td>
<td>1.45 ±0.26</td>
</tr>
</tbody>
</table>

Values are given ± SE; n = number of rats. See text for definitions of groups. *P < 0.05.
filter affecting the large pores (18). By contrast, for exclusive changes in charge selectivity, θ for albumin would change in excess of those for Ficoll55–80Å, because albumin will now, unlike Ficoll55–80Å, be able to permeate also the small pores. In the present study, θs for albumin seemed to change less than θs for Ficoll55–80Å. It thus seems clear that charge selectivity may not be primarily responsible for posttraumatic microalbuminuria. However, it should also, in this context, be noted that with the tissue-uptake technique there is a tendency of overestimating θ to albumin under normal (sham) conditions. The reason for this may be incomplete renal vascular tracer washout at the end of the experiment, and the presence of some free (unbound) iodine in the radiolabeled albumin preparations used. Since the albumin θ is somewhat overestimated in the control situation, the relative changes after surgery and trauma seemed to have been underestimated. At any rate, assuming an albumin θ of the normal glomerular filter to be on the order of 1–2 × 10⁻⁴, the changes posttrauma do still not exceed those measured for Ficoll55–80Å.

Previous studies from our groups strongly indicate that the major barrier to protein permeability of the glomerular filter is not at the level of the podocyte slit diaphragm (10, 17). Thus apparently all the three sequential barriers, i.e., the glomerular basement membrane (GBM) and the two cellular layers, need to interact to form the nearly perfect glomerular permeability barrier normally present (8). However, the way that podocytes interact with the GBM may be crucial. Release of acute proinflammatory mediators and activation of white blood cells by the trauma may interact with the podocytes to produce the changes in their actin cytoskeleton that may alter the shape of the podocyte and the tension that the podocytes exert on the GBM. Also, the integrins linking the podocyte foot processes to the GBM may be acutely involved in the rapid increase in glomerular permeability. Furthermore, it can be speculated that also the endothelial layer may be affected by permeability substances in a way similar to what occurs in peripheral capillaries after release of e.g., histamine, substance P, or cytokines (11, 12, 16).

In conclusion, a laparotomy with or without ensuing muscle trauma caused a rapid and sustained increase in the glomerular permeability to large Ficoll molecules and albumin in a way that seems to reflect a reduced size selectivity of the glomerular filtration barrier, without any primary changes in charge selectivity. According to the two-pore model of glomerular permeability, these changes reflect an increase in the number, and, to some extent, in the radius, of the large pores in the glomerular filter. The rapidity by which these changes occur emphasizes the fact that the permeability of the glomerular filtration barrier is variable over time and can promptly increase in response to inflammation and trauma.

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GRANTS

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REFERENCES

Paper III
Acute hyperglycemia induces rapid, reversible increases in glomerular permeability in nondiabetic rats

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Axellsson J, Rippe A, Rippe B. Acute hyperglycemia induces rapid, reversible increases in glomerular permeability in nondiabetic rats. Am J Physiol Renal Physiol 298: F1306–F1312, 2010. First published March 17, 2010; doi:10.1152/ajprenal.00710.2009.—This study was performed to investigate the impact of acute hyperglycemia (HG) on the permeability of the normal glomerular filtration barrier in vivo. In anesthetized Wistar rats (250–280 g), the left ureter was catheterized for urine collection, while simultaneously blood access was achieved. Rats received an intravenous (iv) infusion of either 1) hypertonic glucose to maintain blood glucose at 20–25 mM (G; n = 8), 2) hyperionic glucose as in 1) and a RhoA-kinase inhibitor (Y-27632; Rho-G; n = 8); 3) 20% mannitol (MANN; n = 7) or 4) hypertonic (12%) NaCl to maintain plasma crystallloid osmotic pressure (πosm) at ~320–325 mosmol/l (NaCl; n = 8) or 3) physiologic saline (SHAM; n = 8). FITC-Ficoll 70/400 was infused iv for at least 20 min before termination of the experiments, and plasma and urine were collected to determine the glomerular sieving coefficients (θ) for polydispers Ficoll (molecular radius 15–80 Å) by high-performance size-exclusion chromatography. In G there was a marked increase in θ for Ficoll15, at 20 min, which was completely reversible within 60 min and abrogated by a Rho-kinase (ROCK) inhibitor, while glomerular permeability remained unchanged in MANN and NaCl. In conclusion, acute HG caused rapid, reversible increases in θ for large Ficolls, not related to the concomitant hyperosmolarity, but sensitive to ROCK inhibition. The changes observed were consistent with the formation of an increased number of large pores in the glomerular filter. The sensitivity of the permeability changes to ROCK inhibition strongly indicates that the cytoskeleton of the cells in the glomerular barrier may be involved in these alterations.

microalbuminuria; RhoA-kinase; podocytes; endothelium; hyperosmolarity

CHRONIC HYPERGLYCEMIA (HG), such as in diabetes mellitus, may cause macro- and microangiopathy with microalbuminuria as an early sign, and, eventually, widespread end-organ damage. The pathophysiological changes behind HG-induced microvascular dysfunction and organ damage are partly elusive, but include 1) the formation of advanced glycation end products (AGE), 2) an abnormal glucose metabolism via the polyol pathway, 3) an increase in diacylglycerol production, which in turn activates PKC, and 4) increased RhoA-kinase (ROCK) activity (6, 8, 22, 23, 28, 34). With respect to renal injury, HG-induced hemodynamic alterations leading to hyperfiltration also contribute. The final common step causing vascular dysfunction during HG includes an increase in oxidative stress caused by an increased formation of reactive oxygen species (ROS) and decreased endothelial nitric oxide (NO) production. All these alterations may lead to microalbuminuria.

In vitro studies on cultured endothelial monolayers, acute HG has been shown to produce barrier dysfunction and (reversible) endothelial albumin leakage. Hempel et al. (11) thus demonstrated a marked increase in (porcine) endothelial monolayer permeability, already after 30 min of acute HG, being completely reversible within 100 min of continued HG. Zuurlewart et al. (35) demonstrated that acute HG can induce marked increases in the transcapillary escape rate (TER) of high-molecular-weight (70 kDa) dextran in mice. In fact, during acute HG the TER of dextran-70 approached that of dextran-40, which is normally mainly eliminated from the circulation by glomerular filtration (1). These data thus strongly suggest a marked increase in dextran-70 elimination by the urine in acute HG. However, the authors interpreted their findings as solely reflecting a generally increased permeability of the endothelial surface layer (glycocalyx). At any rate, the two mentioned studies indicate that acute HG may alter endothelial and glomerular barrier permeability.

On this background, and since we have recently demonstrated that acute anaphylaxis in rats can rapidly and reversibly increase glomerular permeability to high-molecular-weight FITC-Ficol and to albumin (4), we considered it of interest to investigate whether acute HG, under in vivo conditions, can produce similar dynamic increases in glomerular permeability. To exclude the possibility that glomerular barrier function may be altered following increases in plasma osmolarity per se, we also assessed glomerular selectivity following infusions of hypertonic mannitol or NaCl. In addition, to elucidate the dynamics of glomerular permeability changes during HG, glomerular sieving was followed as a function of time during the HG insult. Finally, to find out whether the contractile F-actin cytoskeleton of the cells of the glomerular filter, i.e., the podocytes and the endothelium, may be involved, we investigated the impact of a ROCK inhibitor on HG-induced glomerular barrier alterations.

Glomerular size selectivity was assessed in vivo by measuring the glomerular sieving of iv infused FITC-Ficoll (70/400), a neutral, near-spherical, polydisperse polysaccharide, which is not to a significant extent reabsorbed by the proximal tubules (33). The experiments were especially designed so as to detect changes in the sieving patterns of very large Ficol molecules, by administering predominantly molecules of high molecular weight (MW ~400 kDa). Large Ficol molecules have been shown to exhibit low glomerular permeability properties more or less identical to those of albumin and large native proteins of equivalent chromatographic radii, which are preferentially permeable through “large pores” (shunt pathways) of the glomerular filter (4, 25, 26, 33). Our data demonstrate rapid, reversible increases in glomerular permeability in acute HG, which may have implications for the microalbuminuria seen in diabetic patients with poor glycemic control.

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MATERIALS AND METHODS

Animals

Experiments were performed in 47 male Wistar rats (Möllergard, Lille Stensved, Denmark), with an average body weight of 273.4 ± 2.4 g. The rats had free access to water and standard chow until the day of the experiment. The animal Ethics Committee at Lund University approved the animal experiments.

Surgery

Anesthesia was induced with pentobarbital sodium (60 mg/kg) intraperitoneally (ip), and body temperature was kept at 37°C by a thermostatically controlled heating pad. The tail artery was cannulated (PE-50 cannula) for continuous monitoring of mean arterial blood pressure (MAP) and heart rate (HR) on a polygraph (model 7B, Grass Instruments, Quincy, MA) and for repeated administration of anesthesia (pentobarbital sodium). The left carotid artery was cannulated (PE-50 cannula) for blood sampling and the left and right jugular veins for infusion purposes. Access to the left ureter was obtained through a small (6–8 mm) abdominal incision. Furosemide (0.375 mg/kg, Furosemid, Recip, Sweden) was administered in the tail artery through a small (6–8 mm) abdominal incision. Furosemide (0.375 mg/ml, TdB Consultancy). The bolus dose (FITC-Ficoll: 70, 40 µg; FITC-Ficoll: 400 960 µg; and FITC-inulin: 500 µg) was followed by a constant infusion of 10 ml·kg⁻¹·h⁻¹ (FITC-Ficoll: 70, 20 µg/ml/FITC-Ficoll-400, 0.48 mg/ml; FITC-Inulin, 0.5 mg/ml, and 51Cr-EDTA 0.3 MBq/ml) for at least 20 min before sieving measurements, after which time urine from the left kidney was collected for 5 min, with a midpoint (2.5 min) plasma sample collected.

Glomerular Sieving of FITC-Ficoll-70/400

Glomerular filtration rate (GFR) was measured in the left kidney during the experiment using 51Cr-EDTA. A priming dose of 51Cr-EDTA (0.3 MBq in 0.2 ml iv, Amersham Biosciences, Buckinghamshire, UK) was administered and followed by a continuous infusion (10 ml·kg⁻¹·h⁻¹) of 51Cr-EDTA (0.3 MBq/ml) throughout the experiment. Urine was collected from the left ureter repeatedly during this period, and blood samples, using microcapillaries, were taken to be able to calculate GFR, every 10 min. Radioactivity in blood and urine was measured in a gamma counter (Waters 1480, LKP, Wallac, Turku, Finland). Hematocrit was assessed throughout the experiments to convert blood radioactivity into plasma radioactivity. During the FITC-Ficoll sieving period, GFR was also assessed from the urine clearance of FITC-inulin.

High-Performance Size-Exclusion Chromatography

An HPLC system (Waters, Milford, MA) was used to determine size and concentration of the Ficoll samples. Size exclusion was achieved using an Ultrahydrogel-500 column (Waters). The mobile phase was driven by a pump (Waters 1525), and fluorescence was detected with a fluorescence detector (Waters 2475) with an excitation wavelength at 492 nm and an emission wavelength at 518 nm. The samples were loaded to the system with an autosampler (Waters 717 plus), and the system was controlled by Breeze Software 3.3 (Waters). The column was calibrated with Ficoll and protein standards described in a previous paper (2).

Transmission Electron Microscopy of Rat Glomeruli Exposed to HG vs. Control

Biopsies from kidneys were taken using a human (percutaneous) biopsy needle (True Core II Biopsy Instrument, Angiotech Medical Device Technologies, Gainesville, GA). Biopsies were immediately placed in fixative (1.5% glutaraldehyde and 1.5% paraformaldehyde in 0.1 M Sorensen phosphate buffer (pH 7.2)) and left overnight. After fixation, biopsies were rinsed in buffer, postfixed in 1% osmiumtetroxide (OsO₄) for 1 h, and dehydrated using graded acetone solutions and embedded in Polarisi 812 (Polaron). Ultrathin sections (60–80 nm) were cut using a LKB Supernova ultramicrotome (Reichert Jung, Vienna, Austria) and placed on thin-bar copper grids and stained with uranyl acetate and lead citrate. The sections were examined using a Philips CM-10 transmission electron microscope (Philips Scientific, Eindhoven, Netherlands).

Calculations

The urinary excretion of 51Cr-EDTA and FITC-inulin per minute (U × V) divided by the concentration of tracer in plasma (P) was
used to calculate GFR, where \( U_t \) represents the tracer concentration in urine, and \( V_u \) the flow of urine per minute. Ficoll sieving coefficients (\( \theta \)) were obtained by analyzing high-performance size-exclusion chromatography (HPSEC) curves from the plasma \( (C_{pF}) \) and urine sample for each experiment. The urine concentration vs. the Stokes-Einstein radius \( (a_e) \) curve was divided by the inulin concentration to obtain the primary urine concentration \( (C_{uF}) \). \( \theta \) for each \( a_e \) was calculated by dividing \( C_{uF} \) by \( C_{pF} \). A two-pore model (17, 24, 29) was used to analyze the \( \theta \) data for Ficoll (molecular radius 15–80 Å). A nonlinear least-squares regression analysis was used to obtain the best curve fit, using scaling multipliers, as described at some length previously (17).

**Statistical Analysis**

Values are presented as means ± SE. Differences among groups were tested using nonparametric analysis of variance with the Kruskal-Wallis U-test. Bonferroni corrections for multiple comparisons were made. Significance levels were set at \( *P < 0.05, **P < 0.01, \) and ***\( P < 0.001. \) All statistical calculations were made using SPSS 17.0 for Windows (SPSS, Chicago, IL).

**RESULTS**

**Hemodynamic Parameters**

All the experimental groups showed a stable mean arterial pressure (Fig. 1) and heart rate (not shown) over time.

\( \pi_{crv} \) and Blood Glucose

Results from blood glucose and plasma crystalloid osmotic measurements in the various groups as a function of time are listed in Tables 1 and 2, respectively. During HG, blood glucose increased by 14–18 mM, while the hyperosmolar insults (NaCl, MANN) caused an increase in plasma osmolarity on the order of 12–14 mosmol/l, which in NaCl matched the measured increase in plasma Na \((+7 \text{ mmol/l})\).

![Mean Arterial Pressure](image)

Fig. 1. Mean arterial pressure (MAP) vs. time in the experimental groups and in the SHAM group. During high glucose (HG) and concomitant Rho-kinase inhibition (in Rho-G), there was a fall in MAP, while it was largely unchanged in all other groups. Solid line and squares, SHAM; dashed line and filled circles, G; dotted line and triangles, mannitol (MANN); finely dashed line and stars, NaCl; and dashed-dotted line and pentagons, Rho-G.

**Table 1. Blood glucose concentration (mmol/l) as a function of time during 20 min of HG and, sequentially, at G-5, G-20, and G-60, respectively**

<table>
<thead>
<tr>
<th>Time</th>
<th>( G ) ((n = 8))</th>
<th>Rho-G ((n = 8))</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 min</td>
<td>5.26 ± 0.27</td>
<td>4.86 ± 0.13</td>
</tr>
<tr>
<td>10 min</td>
<td>21.26 ± 0.89***</td>
<td>21.01 ± 0.55***</td>
</tr>
<tr>
<td>20 min</td>
<td>22.81 ± 0.87***</td>
<td>21.69 ± 0.37***</td>
</tr>
<tr>
<td>60 min</td>
<td>23.20 ± 0.90***</td>
<td>21.91 ± 0.63***</td>
</tr>
</tbody>
</table>

**Values are means ± SE.** HG, high glucose. Statistical differences are indicated for the test period vs. baseline (time 0). The significance level is ***\( P < 0.001. \)**

**GFR**

GFR (Fig. 2) remained more or less stable in all groups, but tended to slightly increase in SHAM \([0.71 ± 0.05 \text{ ml·min}^{-1}·g^{-1} \text{(kidney)}] \) to \([0.76 ± 0.06 \text{ ml·min}^{-1}·g^{-1}];\) not significant).

\( \theta \) for FITC-Ficoll

Figure 3 demonstrates \( \theta \) vs. Stokes-Einstein radius \((a_e)\) curves for Ficoll molecules ranging in radius from 15 to 80 Å for G, MANN and NaCl vs. SHAM at 20 min. In the \( a_e \) range 55–80 Å, G showed a clearly increased \( \theta \), whereas \( \theta \) for MANN and NaCl remained unchanged compared with SHAM. For Ficoll-\( 70_{\text{KDa}} \), \( \theta \) thus increased from \( 2.41 \times 10^{-5} ± 7.57 \times 10^{-6} \) to \( 1.16 \times 10^{-4} ± 3.87 \times 10^{-5} (P < 0.01) \) in G, whereas \( \theta \) for Ficoll-\( 70_{\text{KDa}} \) in MANN and NaCl remained more or less unchanged at \( 2.88 \times 10^{-5} ± 7.14 \times 10^{-6} \) and \( 3.66 \times 10^{-5} ± 5.14 \times 10^{-6}, \) respectively. This was also the case for Rho-G, in which the glomerular Ficoll sieving curve was more or less the same as for SHAM (Fig. 4). For Ficoll-\( 70_{\text{KDa}} \) \( \theta \) was thus \( 2.84 \times 10^{-5} ± 6.81 \times 10^{-6} \) at 20 min of HG under Rho-kinase inhibition.

**Table 2. Plasma crystalloid osmotic pressure as a function of time in the 2 hyperosmolar groups and plasma Na\(^+\) concentration**

<table>
<thead>
<tr>
<th>Time</th>
<th>Plasma Crystalloid Osmotic Pressure, mosmol/l</th>
<th>Na(^+) Concentration, mmol/l ((n = 8))</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 min</td>
<td>308.7 ± 0.61***</td>
<td>141.4 ± 0.42***</td>
</tr>
<tr>
<td>10 min</td>
<td>320.6 ± 1.80***</td>
<td>147.9 ± 0.35***</td>
</tr>
<tr>
<td>20 min</td>
<td>322.1 ± 2.62***</td>
<td>148.8 ± 0.37***</td>
</tr>
</tbody>
</table>

**Values are means ± SE.** Statistical differences are indicated for values after 10 and 20 min versus time 0. Significance levels are ***\( P < 0.001. \)**
Figure 5 shows θ for Ficoll molecules from 60 to 80 Å in radius during HG as a function of time, i.e., at 5, 20, and 60 min (G-5, G-20, and G-60, respectively). HG caused significant increases in θ for large Ficoll molecules at 20 min, and these changes were completely reversible within 60 min. For Ficoll70Å, G-20 thus showed a sieving coefficient of $2.36 \times 10^{-4} \pm 8.03 \times 10^{-5}$, which was reversed to $1.64 \times 10^{-5} \pm 4.5 \times 10^{-6}$ at G-60 ($P < 0.001$).

Two-Pore Modeling

The best curve fits of θ vs. $a_e$ for Ficoll according to the two-pore model were obtained using the parameters listed in Tables 3 and 4. Data demonstrate that the fractional hydraulic conductance accounted for by the large pores ($\theta_L$) had increased almost threefold in G compared with SHAM ($P < 0.05$), indicating the formation of more large pores in the glomerular filter during HG. The fractional fluid flow through the large pores (large-pore volume flow/GFR) was also markedly increased in G compared with SHAM ($P < 0.05$), which was also the case for the large pore radius ($P < 0.05$).

Transmission Electron Microscopy

Results from transmission electron microscopy (TEM) of samples from HG and SHAM animals are shown in Fig. 6. All structures of the glomerular filtration barrier were investigated at a threefold higher magnification than that demonstrated in Fig. 6. There were no significant morphological alterations observed at this magnification with respect to either endothelial cells, podocytes, or the glomerular basement membrane in G (at 20 min) compared with SHAM, despite the increase in glomerular permeability in G.

DISCUSSION

This is, to our knowledge, the first direct demonstration in vivo that acute HG, independent of the concomitant hyperos-
molarity, can cause rapid, marked, and reversible increases in glomerular permeability to macromolecules. Furthermore, the permeability increases observed were completely abrogated by a ROCK inhibitor. This strongly indicates that the contractile F-actin cytoskeleton of the cells of the glomerular filtration barrier, i.e., the podocytes and/or the fenestrated endothelium, may be directly involved in this acute, dynamic glomerular permeability response. However, from a morphological point of view the permeability alterations were subtle, as electron microscopy of the glomerular filter did not demonstrate any gross alterations of any of the components of the filtration barrier during HG.

These fully reversible permeability changes in response to acute HG in nondiabetic rats should be distinguished from the partly nonreversible glomerular alterations occurring as a consequence of chronic HG in diabetes. In poorly insulin-treated streptozotocin (STZ) diabetic rats, in which blood glucose was maintained at ~20 mM for either 3 or 9 wk, we were not able to find any changes in glomerular permeability to albumin after 3 wk of HG, although the animals showed an increased urinary albumin excretion rate (AER) due to a tubular reabsorption defect (27). However, after 9 wk of HG there was a marked reduction in glomerular size selectivity accompanying the large increase in AER, consistent with an increased formation of “large pores” (shunt pathways) in the glomerular filtration barrier. It is likely that the latter changes may be due to (partly) nondynamic structural alterations in the glomerular filter. In recent years, much focus has been on the role of the decline in podocyte number in diabetic nephropathy, largely paralleling the degree of proteinuria and disease progression (15). It is thus likely that an important component of the glomerular injury following on chronic HG, besides the well-established changes in the glomerular basement membrane and the glomerular mesangium, may be related to pathological changes involving the podocytes.

The exact mechanisms of the rapid increases in glomerular permeability observed, and to what extent podocytes or endothelial cells, or both, are involved, are not known. On a longer time scale, i.e., over 1 or several days, there is evidence that HG induces activation of members of the PKC superfamily, especially PKC-α and PKC-β, which may play a role in the pathophysiology of long-term renal diabetic manifestations (20). Hence, in STZ diabetic rats and in the db/db mouse model of type 2 diabetes, PKC-β inhibition using ruboxistaurin was able to prevent albuminuria (12, 13). However, studies in patients with type 2 diabetes have been much less equivocal, suggesting that ruboxistaurin has only little effect on HG-induced albuminuria in humans (5, 31). In monolayers of porcine aortic, i.e., nonrenal, endothelium in vitro, PKC-α seems to be mainly responsible for the permeability actions of HG, and unspecific PKC inhibition completely abrogated the acute endothelial permeability increases induced by HG in this system (11).

Even though PKC activation may be pivotal in the chronic permeability actions of HG, we decided in this study to test whether the cellular F-actin cytoskeleton in podocytes and endothelium be involved in the acute response to HG. There is accumulating evidence that members of the Rho family of small GTPases regulate both the actin cytoskeleton organization and the integrity of the intracellular junctions (21). Rho-A, and its downstream effector ROCK, act, at least in part, by increasing the phosphorylation of myosin light chain, which in nonmuscle cells leads to actomyosin contraction. For example, thrombin-induced endothelial permeability increases have been attributed to stress fiber formation and subsequent actomyosin-mediated contraction of cells (16) as well as changes in the distribution of intercellular adhesion molecules, such as cadherins and catenins (7). Beneficial effects of ROCK inhibition were recently demonstrated in (murine) puromycin aminonucleoside nephrosis, in acute renal failure in rats after ischemia-reperfusion, and in cat skeletal muscle in vivo affected by slight inflammation (18, 30, 32). In the present study, the complete abrogation of HG-induced permeability increases by a ROCK inhibitor strongly indicates that HG causes reversible actomyosin contraction in podocytes and/or endothelial cells and that the RhoA/ROCK system may be directly involved in this process.

As also previously demonstrated (11), the permeability actions of HG were found to be highly transient in nature. This is similar to the action of a number of various permeability substances interacting with the endothelium, such as histamine, substance-P, or thrombin (10, 19), and with the pattern of

---

### Table 3. Two-pore parameters

<table>
<thead>
<tr>
<th></th>
<th>SHAM (n = 8)</th>
<th>G (n = 8)</th>
<th>MANN (n = 7)</th>
<th>NaCl (n = 8)</th>
<th>Rho-G (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r, Å</td>
<td>46.1 ± 0.11</td>
<td>45.9 ± 0.18</td>
<td>46.6 ± 0.22</td>
<td>46.6 ± 0.17</td>
<td>45.3 ± 0.18*</td>
</tr>
<tr>
<td>r, Å</td>
<td>118.4 ± 7.66</td>
<td>164.6 ± 14.64</td>
<td>119.3 ± 9.16</td>
<td>132.4 ± 4.49</td>
<td>114.2 ± 8.34</td>
</tr>
<tr>
<td>0 Å/10Å</td>
<td>3.63 ± 0.59</td>
<td>8.13 ± 1.88*</td>
<td>4.16 ± 1.24</td>
<td>3.48 ± 0.38</td>
<td>4.48 ± 0.76</td>
</tr>
<tr>
<td>Jv/GFR × 10^5</td>
<td>9.52 ± 1.70</td>
<td>25.8 ± 6.61*</td>
<td>13.2 ± 3.22</td>
<td>10.0 ± 1.03</td>
<td>11.3 ± 1.59</td>
</tr>
<tr>
<td>A/A'X cm^2/g × 10^-5</td>
<td>2.85 ± 0.13</td>
<td>1.56 ± 0.15</td>
<td>1.85 ± 0.08</td>
<td>2.35 ± 0.16</td>
<td>4.21 ± 0.23*</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = number of rats. Symbols are given in the text.

---

### Table 4. Two-pore parameters

<table>
<thead>
<tr>
<th></th>
<th>G-5 (n = 8)</th>
<th>G-20 (n = 8)</th>
<th>G-60 (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r, Å</td>
<td>46.3 ± 0.20</td>
<td>46.3 ± 0.16</td>
<td>46.0 ± 0.12</td>
</tr>
<tr>
<td>r, Å</td>
<td>124.5 ± 5.47</td>
<td>175.6 ± 7.47**</td>
<td>114.3 ± 5.43</td>
</tr>
<tr>
<td>0 Å/10Å</td>
<td>3.27 ± 0.60</td>
<td>11.3 ± 3.93*</td>
<td>2.26 ± 0.18</td>
</tr>
<tr>
<td>Jv/GFR × 10^5</td>
<td>9.28 ± 1.88</td>
<td>26.1 ± 7.98*</td>
<td>5.8 ± 0.67</td>
</tr>
<tr>
<td>A/A'X cm^2/g × 10^-5</td>
<td>3.30 ± 0.37</td>
<td>2.50 ± 0.36</td>
<td>2.30 ± 0.28</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = number of rats. Symbols are given in the text.

Statistical difference between SHAM and experimental groups (G-5, G-20, and G-60) are *P < 0.05 and **P < 0.01.
glomerular response in anaphylactic shock (4). Also, podocytes in culture can undergo rapid, reversible changes in shape due to acute actin reorganization following RhoA and PKB signaling, as recently demonstrated in vitro after exposure of podocytes to hemopexin (14). Whether podocytes and/or endothelial cells are affected by acute HG, the clinical implications of rapid bouts of glomerular permeability increases following HG are that repeated episodes of postprandial HG, in e.g., poorly regulated diabetes, may cause increased levels of microalbuminuria. However, as discussed above, continuous long-term HG seems to cause more permanent lesions affecting the structure and function of the glomerular filter, which may occur independently of the phenomena described in this article.

In a number of previous studies, we have been able to simultaneously assess $\text{Ficoll}^{50\text{--}80\text{Å}}$ for high-molecular-weight Ficoll and $\text{Albumin}^{50\text{--}80\text{Å}}$ for radiolabeled albumin (RISA). We have demonstrated a more or less perfect coupling between these two parameters (3, 4, 26, 27). Thus, whenever there was an increase in $\text{Ficoll}^{50\text{--}80\text{Å}}$, there was a parallel increase in $\text{Albumin}^{50\text{--}80\text{Å}}$ for albumin. This is because both native (negatively charged) albumin and high-molecular-weight Ficoll molecules apparently share the same pathways in the glomerular filter, namely, shunt pathways (large pores). In the present study, we chose not to study albumin because of unexpectedly high levels of free iodine and denaturated protein forming in the albumin preparation at disposal. The previously established tissue uptake technique (17) requires that the fraction of free iodine be <0.1%, which could not be achieved in the present experiments. So far, however, we have not found an “uncoupling” of increases in $\text{Ficoll}^{50\text{--}80\text{Å}}$ vs. albumin, except during moderate ischemia-reperfusion injury, where $\text{Ficoll}^{50\text{--}80\text{Å}}$ increased slightly less than that for albumin (26). Thus, given the close coupling of $\text{Ficoll}^{50\text{--}80\text{Å}}$ for albumin and $\text{Ficoll}^{50\text{--}80\text{Å}}$ we have in this study considered it safe to rely on the latter as an indicator of glomerular permeability.

The absence of gross morphological changes in electron micrographs of glomeruli exposed to HG is intriguing. After all, the observed changes were in the microalbuminuria range, and the normal $\text{Ficoll}^{50\text{--}80\text{Å}}$ to albumin is only on the order of $1\cdot10^{-4}$ (4, 9, 17). According to the two-pore theory of glomerular permeability this implies that there is only one large pore (shunt pathway) per approximately one million of the small pores. Given the very low abundance of shunt pathways, even a three- to fourfold increment in large pore number may be hard to detect by morphological techniques. Alternatively, the changes observed could also be interpreted in terms of an altered endothelial glycocalyx, not visible via routine electron microscopy. If this were the case, then the glycocalyx would have to be rapidly degraded and equally rapidly regenerated to account for the reversible changes in glomerular permeability observed. While this is quite possible, it is less likely, since the permeability changes were abrogated by ROCK inhibition, conceivably affecting the cellular cytoskeleton. Still, to the extent that the glycocalyx may affect intracellular signaling via the RhoA/ROCK system, this possibility cannot be completely ruled out.

In summary, acute hyperglycemia caused marked, reversible increases in glomerular permeability to macromolecules appearing within 20 min in non diabetic rats. These alterations occurred independently of the concomitant hyperosmolality and were abrogated by a ROCK inhibitor, interfering with the actin cytoskeleton of the cellular layers of the glomerular filter. The present data may explain the link between poorly controlled diabetes, with repeated episodes of HG on the one hand, and microalbuminuria on the other, even before permanent structural changes in the diabetic glomerular filtration barrier have started to appear.
ACKNOWLEDGMENTS

We gratefully acknowledge Kerstin Wihlborg for the skillful typing of the manuscript and Lina Gefors and Eric Carlsmalm (Dept. of Clinical Sciences, Electron Microscopy Unit, Lund University Hospital, Lund, Sweden) for excellent technical assistance with electron microscopic preparation and TEM. We are grateful to Mitsubishi Pharmaceutical Corp. (Osaka, Japan) via Per-Olof Grände (Dept. of Anesthesia and Intensive Care, University of Lund and University Hospital of Lund, Lund, Sweden) for the supply of the Rho-kinase inhibitor Y-27632.

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14. Lennon R, Singh A, Welsh GI, Coward RJ, Satchell S, Ni L, Mathieson PW, Bakker WW, Saleem MA. Hemopexin induces nephrin-depen-
Transient and sustained increases in glomerular permeability following ANP infusion in rats

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Axellson J, Rippe A, Rippe B. Transient and sustained increases in glomerular permeability following ANP infusion in rats. Am J Physiol Renal Physiol 300: F24–F30, 2011. First published October 13, 2010; doi:10.1152/ajprenal.00347.2010.—The present study was performed to investigate the effects of systemic atrial natriuretic peptide (ANP) infusion on the glomerular permeability to macromolecules in rats. In anesthetized Wistar rats (250–280 g), the left urether was cannulated for urine collection while simultaneously blood access was achieved. Rats were continuously infused intravenously with ANP [30 ng·kg⁻¹·min⁻¹ (Lo-ANP; n = 8) or 800 ng·kg⁻¹·min⁻¹ (Hi-ANP; n = 10)] or 0.9% NaCl (SHAM; n = 16), respectively, and with polydisperse FITC-Ficoll-70/400 (molecular radius 13–90 Å) and¹⁵Cr-EDTA for 2 h. Plasma and urine samples were taken at 5, 15, 30, 60, and 120 min of ANP infusion and analyzed by high-performance size-exclusion chromatography (HPLC) for determination of glomerular sieving coefficients (θ) for Ficoll. GFR was also assessed (¹⁵Cr-EDTA). In Hi-ANP, there was a rapid (within 5 min), but bimodal, increase in glomerular permeability, θ, to high-molecular-weight Ficoll thus reached a maximum at 15 min, after which θ returned to near control at 30 min, to again increase moderately at 60 and 120 min. In Lo-ANP, there was also a rapid, reversible increase in glomerular θ, returning to near control at 30 min, followed by just a tendency of a sustained increase in permeability, but with a significant increase in “large-pore” radius. In conclusion, in Hi-ANP there was a rapid increase in glomerular permeability, with an early, partly reversible permeability peak, followed by a (moderate) sustained increase in permeability. In Lo-ANP animals, only the initial permeability peak was evident. In both Lo-ANP and Hi-ANP, the glomerular sieving pattern observed was found to mainly reflect an increase in the number and radius of large pores in the glomerular filter. capillary permeability; Ficoll; glomerular filtration; glomerular sieving coefficient

PLASMA VOLUME OVERLOAD, in conjunction with e.g., congestive heart failure, induces an increased secretion to the circulation of atrial natriuretic peptide (ANP) from the heart upon atrial stretch. By its natriuretic, diuretic, and vasodilating properties, ANP is believed to act physiologically as a compensatory hormone protecting against plasma volume expansion (9, 11, 29). Furthermore, in extrarenal tissues ANP induces a fluid shift from the vasculard to the extravascular space, causing increases in hematocrit and plasma protein concentration in nephrectomized rats (2). Although these effects can be related to vasodilatation, and hence, to increases in capillary surface area and in microvascular pressure, there is now good evidence that ANP directly affects capillary permeability to proteins (11, 12, 25, 29, 34) and microvascular hydraulic conductance (16).

Microalbuminuria (i.e., moderately elevated albumin excretion rates, ranging from 20 to 200 μg/min in humans) is a common feature during exercise, posttrauma (4, 14) or after surgery (21), and in systemic inflammation (6), but also in congestive heart failure and following myocardial infarction (15, 23). In the latter conditions, microalbuminuria has been attributed to permeability effects mediated via ANP. Intravenous (iv) infusion of ANP in anesthetized rats thus resulted in increases in urinary albumin/insulin concentration ratios for the dose of 0.5 μg·min⁻¹·kg⁻¹·body wt (BW) and in marked albuminuria for a dose of 1 μg·min⁻¹·kg⁻¹ (22). The exact (patho)physiology of ANP-induced albuminuria is not known. Some of the proteinuric actions of ANP have been attributed to reductions in the proximal tubular reabsorption of albumin, but whether, or to what extent, glomerular permeability per se is affected, either via charge-selective or size-selective glomerular changes, needs to be further elucidated.

On that background, we investigated the functional behavior of the glomerular filtration barrier in response to continuous iv infusion of ANP in rats. A low, “physiological” (Lo-ANP) and a high, “supraphysiological” ANP (Hi-ANP) dose were investigated. Glomerular size selectivity was assessed in vivo using FITC-Ficoll 70/400, a neutral polysaccharide which is not significantly reabsorbed by the proximal tubules, to assess the glomerular sieving coefficient (θ), i.e., the filtrate-to-plasma concentration ratio, for a broad spectrum of molecular radii, with emphasis on the glomerular sieving pattern of molecules of high molecular weight (MW—400,000). A rapid, reversible increase in glomerular permeability was noted for both Lo-ANP and Hi-ANP animals, in the latter followed by a moderate, but sustained increase in glomerular permeability.

MATERIALS AND METHODS

Animals and surgery. Experiments were performed in 34 male Wistar rats (Møllegård, Lille Stensved, Denmark) with an average BW of 267.7 ± 2.8 g. The rats were kept on standard chow and had free access to water until the day of the experiment. The animal Ethics Committee at Lund University approved the animal experiments. The rats were anesthetized with an intraperitoneal injection of pentobarbital sodium, 60 mg/kg, and the animals were placed on a thermostatically controlled heating pad to keep body temperature at 37°C. A tracheotomy was performed to facilitate breathing. The tail artery was cannulated (PE-50 cannula) for blood pressure monitoring and registration of heart rate (HR) on a polygraph (model 7B; Grass Instruments, Quincy, MA) and for repeated injections of maintenance anesthesia (pentobarbital sodium). The left carotid artery and the left and right external jugular veins were cannulated (PE-50 cannula) for blood sampling and infusion purposes, respectively. Access to the left urether was obtained through a small (6–8 mm) abdominal incision. Furosemide (0.375 mg/kg, Furosemid, Recip, Sweden) was administered in the tail artery to increase urine production and facilitate cannulation of the urether, which was used for urine sampling. The latter was dissected free, and a PE-10 (connected to a PE-50) cannula was inserted and secured by a ligature.
Experimental procedures: ANP infusion. All experiments started with an initial resting period of 10–15 min following the cannulation of the left urether. ANP (A8208, lot no. 049K4809, Sigma-Aldrich, St. Louis, MO) was infused iv by either a low dose (30 ng·kg⁻¹·min⁻¹; LO-ANP, n = 8) (34) or a high dose (800 ng·kg⁻¹·min⁻¹; HI-ANP, n = 10). The LO-ANP dose, chosen not to affect mean arterial pressure (MAP) or glomerular filtration rate (GFR), was selected based mainly on two previous studies (30, 34). Tucker et al. (34) found that 20 ng·kg⁻¹·min⁻¹ infused iv in rats resulted in a plasma concentration of 190 pg/ml, which caused moderate increases in the extravasation of radiolabeled albumin to the gut (colon and jejunum), while MAP remained unaltered, despite a reduction in heart rate. Salazar et al. (30) found in dogs that 50 ng·kg⁻¹·min⁻¹ of ANP infusion iv was the highest dose that could be given without a drop in MAP or an increase in GFR. In a pilot study, we found that 50 and 60 ng·kg⁻¹·min⁻¹ of ANP iv slightly reduced MAP. We therefore chose a moderately lower dose, 30 ng·kg⁻¹·min⁻¹, for the LO-ANP group, yielding a calculated plasma ANP level of 200 pg/ml, which is approximately twice the physiological plasma ANP level. From the data of Tucker et al. (34), we could calculate that an iv ANP infusion rate of 800 ng·kg⁻¹·min⁻¹ would produce a plasma concentration of 1.740 pg/ml, which is in the lower range of 2.000–3.000 pg/ml, which have been observed after 25% blood volume expansion in rats with experimental heart failure (10), but higher than observed after 20% plasma volume expansion in rats by another group (24). Furthermore, 800 ng·kg⁻¹·min⁻¹ is about intermediate between the medium and the high doses of ANP infused in rats for studies of ANP-induced albuminuria by Nielsen et al. (22).

For the LO-ANP dose, an initial bolus (4.75 μl of a 0.04 μg/μl ANP solution) was given iv followed by a constant infusion (2.5 μl/min of a 0.0033 μg/μl solution) throughout the experiment (2 h). Also for the HI-ANP dose, an initial bolus (75 μl of a 0.04 μg/μl solution) was given followed by a continuous infusion (5 μl/min of a 0.04 μg/μl solution). For Ficoll sieving experiments, sampling of urine and blood (2 × 70 μl at a time for Ficoll determinations, using hemocrit capillaries, plus 25 μl for 31Cr-EDTA assessments, using precision micro-capillaries) was performed sequentially, at 5, 15, 30, 60, and 120 min, respectively. The blood sampling in hemocrit tubes allowed for simultaneous plasma retrieval and hemocrit determination. In SHAM (n = 16), 0.9% NaCl in a bolus and infusion, mimicking the volume load of the ANP experiments, was given during 2 h with measurements performed at the start (0–5 min; SHAM-5) and at 60 min (SHAM-60) and 120 min (SHAM-120). The total blood volume withdrawn during 120 min was 825 μl (4% of total blood volume) for ANP animals and 495 μl for SHAM animals.

GFR. GFR was measured in the left kidney during the experiment, using 31Cr-EDTA. A priming dose of 31Cr-EDTA (0.3 MBq in 0.2 ml iv, Amersham Biosciences, Buckinghamshire, UK) was administered and followed by a continuous infusion (10 nl·kg⁻¹·h⁻¹) of 31Cr-EDTA (0.37 MBq/ml in 0.9% NaCl) throughout the experiment, which yielded a stable plasma concentration of 0.31Cr-EDTA over time. Urine was collected from the left urether repeatedly during the experiment and blood samples, using microcapillaries, 25 μl at a time (see above), were taken to be able to assess GFR, approximately every 20 min. Radioactivity in blood and urine was measured in a gamma counter (Wizrad 1480, LKP, Wallac, Turku, Finland). Hemocoarties (see above) was assessed throughout the experiments to be able to convert blood radioactivity into plasma radioactivity. During the FITC-Ficoll sieving periods (see below), GFR was also assessed from the urine clearance of FITC-Inulin. The urinary excretion of 31Cr-EDTA and FITC-Inulin per minute (U, V, or VU) divided by the concentration of tracer in plasma (P) was used to calculate GFR where U represents the tracer concentration in urine, and V the flow of urine per minute. Since the variability (coefficient of variation) for FITC-Inulin-assessed GFR was slightly higher than that for 31Cr-EDTA-assessed GFR, we have presented the latter consistently throughout this study.

Glomerular sieving of FITC-Ficoll. A mixture of FITC-Ficol-70 (10 mg/ml) and FITC-Ficol-400 (10 mg/ml) (TdB Consultancy, Uppsala, Sweden) in a 1:24 relationship was administered as a bolus dose together with FITC-Inulin (10 mg/ml, TdB Consultancy). The bolus dose [40 μg (FITC-Ficol-70); 960 μg (FITC-Ficol-400); and 500 μg (FITC-Inulin)] was followed by a constant infusion of 10 ml kg⁻¹·h⁻¹ (FITC-Ficol-70, 20 μg/ml; FITC-Ficol-400, 0.48 mg/ml; FITC-Inulin, 0.5 mg/ml; and 31Cr-EDTA, 0.3 MBq/ml) for at least 20 min before sieving measurements, after which urine from the left kidney was collected for 5 min, with a midpoint (2.5 min) plasma sample collected. During the constant infusion of FITC-Ficol-70/400, Ficoll molecules >50 Å in radius mostly increased their concentration, while Ficoll molecules <30 Å decreased their concentrations over the course of the infusion. During a 5-min period, however, these changes were <1%. The midpoint plasma sample taken during the 5 min of urine collection would thus rather accurately reflect the average plasma concentration of Ficoll during each urine sampling period.

High-performance size-exclusion chromatography. Plasma and urine samples were assessed on a size-exclusion high-performance chromatography system (Waters, Milford, MA) with an Ultrahydrogel 500 column (Waters) and calibrated as described in detail previously (5). The mobile phase was driven by a pump (Waters 1525), and fluorescence was detected with a fluorescence detector (Goltermann 2475) with an excitation wavelength at 492 nm and an emission wavelength at 518 nm. The samples were loaded to the system with a autosampler (Waters 717 plus), and the system was controlled by Breeze Software 3.3 (Waters).

Glomerular Ficol θ vs. Stokes-Einstein radius. The θ is defined as the concentration of solute in the ultrafiltrate over that in plasma, i.e., a filtrate-to-plasma concentration ratio. Ficol θ were obtained by analyzing HPLC-curves, i.e., Ficol concentration vs. elution time (translated into the relative distribution volumes in the column of the different size Ficoll molecules) from the plasma (Cpθ) and urine samples for each experiment. The urine Ficol concentration vs. the Stokes-Einstein radius (aθ) curve was divided by the Inulin concentration to obtain the primary urine concentration of Ficol (Cuw). For each aθ, θ was then calculated by dividing Cuθ by Cpθ.

Two-pore analysis. A two-pore model (19, 26, 28) was used to analyze the θ data for Ficol (molecular radius 15–80 Å). A nonlinear least-squares regression analysis was used to obtain the best curve fit, using scaling multipliers, as described at some length previously (27). The major parameters of the two-pore model are (1) the small-pore radius (rs), 2) the large-pore radius (rl), 3) the unrestricted pore area over unit diffusion path-length (Aθ/Δx), and 4) the fraction of the glomerular ultrafiltration-coefficient accounted for by the large pores (aθ). The latter parameter reflects the abundance of “large pores” in the glomerular filter and is calculated from the fractional GFR diverted through the large pores, i.e., Jθ/GFR. For stable GFRs, this parameter may be regarded as a more “robust” parameter than aθ, αθ, and Jθ/GFR are mathematically obtained by extrapolating the “flat” portion of the Ficol sieving curve for molecules >50 Å in radius, i.e., the rl curve, back to the ordinate scale (i.e., to 0 Å). This imparts some uncertainty to aθ, especially if rl is markedly altered. After a large increase in rl, aθ (Jθ/GFR) may tend to be slightly underestimated. By contrast, if rl is reduced, then aθ and Jθ/GFR may be overestimated. The parameter, rs, is mainly dependent on sieving data (θ) close to the inflection point between the rl curve and the θ curve, i.e., for θ values for ur ranging between ~40 and ~46 Å. Aθ/Δx is a diffusive parameter reflecting the surface area of the small pores. A high Aθ/Δx (or a low GFR) will displace the sieving curve for Ficol radii between 20 and 40 Å to the right, thereby causing a “shaper” θ curve with a sharp cut-off. A low Aθ/Δx (or a high GFR) will displace the rl curve to the left, creating a more “shallow” θ curve (27).
post hoc tested using the Mann-Whitney U-test. Bonferroni corrections for multiple comparisons were made. Significance levels were set at \* \(P < 0.05\), \** \(P < 0.01\) and \*** \(P < 0.001\). All statistical calculations were made using SPSS 18.0 for Windows (SPSS, Chicago, IL).

RESULTS

MAP and HR. SHAM and Lo-ANP animals showed a stable MAP and HR (not shown) throughout the experiment. Hi-ANP animals showed an early decrease in MAP just after start of the infusion of ANP from 97.5 (85–111.3) to 77.5 (73.8 – 87.5) mmHg, the MAP remaining depressed during the rest of the experiment, reaching 65.0 (65–75) mmHg at 120 min. A decrease in HR from 340 (320 –385) to 275 (248 –303) beats/min; \* \(P < 0.01\) was also seen in the Hi-ANP group at 120 min of the experiment.

GFR. GFR (Fig. 1 and Table 1) remained more or less stable in all groups, but tended to slightly increase in SHAM from 0.65 (0.62–0.82) to 0.84 (0.73–0.93) ml·min\(^{-1}\)·g (kidney)\(^{-1}\); not significant.

\(\theta\) of FITC-Ficoll. Figure 2 shows the \(\theta\) for Ficoll\(_{70\text{Å}}\) in Hi-ANP (top), Lo-ANP (middle), and SHAM (bottom), respectively, as a function of time, i.e., at 5, 15, 30, 60, and 120 min. There was a bimodal permeability response with an early permeability peak, i.e., an increase in \(\theta\) for Ficoll\(_{70\text{Å}}\) vs. SHAM (horizontal line) at 5 and 15 min, reversing to near SHAM values at 30 min. This was later followed by a more sustained, low-grade increase in \(\theta\) Ficoll\(_{70\text{Å}}\) at 60 and 120 min, which was statistically significant in Hi-ANP (at 60 min).

**Table 1. Median and 1st–4th quartile ranges for GFR as a function of time in Fig. 1**

<table>
<thead>
<tr>
<th>Time, min</th>
<th>SHAM</th>
<th>Time, min</th>
<th>Lo-ANP</th>
<th>Hi-ANP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.65 (0.62–0.82)</td>
<td>0.72 (0.43–0.92)</td>
<td>0.72 (0.64–0.80)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.70 (0.63–0.73)</td>
<td>0.62 (0.57–0.73)</td>
<td>0.71 (0.55–0.85)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.59 (0.57–0.76)</td>
<td>0.63 (0.45–0.71)</td>
<td>0.65 (0.52–0.79)</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.69 (0.59–0.87)</td>
<td>0.74 (0.53–0.84)</td>
<td>0.55 (0.49–0.69)</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.83 (0.78–0.87)</td>
<td>0.68 (0.54–0.79)</td>
<td>0.71 (0.61–0.79)</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>0.84 (0.73–0.93)</td>
<td>0.74 (0.54–0.84)</td>
<td>0.71 (0.60–0.78)</td>
<td></td>
</tr>
</tbody>
</table>

GFR, glomerular filtration rate; ANP, atrial natriuretic peptide; SHAM, control animals; Lo-ANP and Hi-ANP, low-dose ANP- and high-dose ANP-treated animals, respectively.
Ficoll80Å, respectively, are given in Table 2. The increase in glomerular permeability did not reach statistical significance in Lo-ANP dose. Even though the second, more sustained increase in barrier permeability, which was significant for the high ANP dose. This was followed by a very moderate, sustained increase in ANP in the rat. The essential result of the study is that both low and high ANP concentrations caused a rapid (within 5 min), partially reversible increase in glomerular permeability. This was followed by a very moderate, sustained increase in barrier permeability, which was significant for the high ANP dose. Even though the second, more sustained increase in permeability did not reach statistical significance in Lo-ANP animals, there were indications of increases in $r_L$ throughout the intervention in this group. Thus, according to a two-pore model of glomerular permeability, the sieving patterns observed during the first and second phase of ANP infusion were compatible with an increase in the number and/or radius of large pores in the glomerular filter without any primary alterations in glomerular charge selectivity. Furthermore, a dose dependence of ANP action on glomerular permeability was evident.

ANP is a small peptide secreted by the heart upon atrial stretch and/or myocardial ischemia. The acute effects of ANP are both renal and nonrenal. The renal effects include an increased GFR and an increased renal excretion of sodium and water, preferentially in the distal part of the nephron (9). The nonrenal effects of ANP include vasodilation, by relaxation of vascular smooth muscle, and an acute increase in vascular permeability via receptors in the microvascular endothelium (25). Due to the diuretic and natriuretic effects of ANP, it would cause plasma protein upconcentration and increases in plasma oncotic pressure that would mobilize fluid from the interstitium, counteracting any reductions in plasma volume. However, due to the nonrenal effects of ANP, mainly the increases in vascular permeability, plasma volume overload is counteracted by permitting an increased flux of fluid and proteins to the interstitium. Both ANP and the closely related B-type natriuretic peptide (BNP) act on the ANP/BNP receptor guanylyl cyclase-A (GC-A) signaling via a guanylyl cyclase pathway. Deletion of this receptor has been found to result in various degrees of hypertension, plasma volume expansion, and cardiac hypertrophy. In endothelial cell-specific GC-A knockout mice, iv ANP failed to increase endothelial permeability and failed to cause a hypovolemic and hypertensive response, despite intact renal responses to ANP (29). This strongly indicates that increases in endothelial permeability are critically involved in ANP-induced reductions of plasma volume during volume overload.

While the rationale for systemic ANP actions on vascular permeability is logical, the effects on glomerular permeability are more enigmatic. Previous studies have indeed demonstrated that systemic ANP infusion in anesthetized rats can markedly increase urinary albumin excretion, although the exact mechanisms of this proteinuric action have not been elucidated (22). The direct assessment of glomerular permeability in the present study supports the concept that ANP-induced albuminuria is a consequence of a direct effect on the glomerular filtration barrier, leading to a partly reversible increase in the radius and number of large glomerular pores without any primary effects on glomerular charge selectivity.

We have previously demonstrated that anaphylaxis (8) and hyperglycemia (7) can induce rapid, reversible changes in glomerular permeability similar to those induced by ANP. The hyperglycemic permeability response could be abrogated by a

**Table 2. Median and ranges of $\theta$ for Ficoll60Å, Ficoll70Å, and Ficoll80Å in SHAM, Lo-ANP, and Hi-ANP, respectively**

<table>
<thead>
<tr>
<th></th>
<th>SHAM 60 min</th>
<th>Lo-ANP</th>
<th>Hi-ANP</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 Å</td>
<td>$3.28 \times 10^{-5}$</td>
<td>$1.35 \times 10^{-6}$</td>
<td>$3.10 \times 10^{-6}$</td>
</tr>
<tr>
<td>70 Å</td>
<td>$2.19 \times 10^{-4}$</td>
<td>$1.14 \times 10^{-4}$</td>
<td>$2.86 \times 10^{-4}$</td>
</tr>
<tr>
<td>80 Å</td>
<td>$1.91 \times 10^{-3}$</td>
<td>$9.98 \times 10^{-4}$</td>
<td>$2.72 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Statistical difference between SHAM and experimental groups: *$P < 0.01$, †$P < 0.001$.  

\[\text{Fig. 3. Median curves depicting } \theta \text{ vs. Stokes-Einstein radius (}a_r\text{) for SHAM-60 and Lo-ANP and Hi-ANP, respectively, at 15 min after start of the ANP infusion. Medians and ranges of } \theta \text{ values for Ficoll60Å, Ficoll70Å, and Ficoll80Å, respectively, are given in Table 2. The increase in glomerular permeability to ANP occurred in a more or less dose-dependent fashion during the initial (0–30 min) permeability peak.} \]

10$^{-5.1.62 \times 10^{-5}} (P < 0.01)$ and to 2.86 $\times 10^{-4}$ (9.93 $\times 10^{-5}$–5.49 $\times 10^{-4}$ ($P < 0.001$) at 15 min for Lo-ANP and Hi-ANP, respectively.

Two-pore modeling. The best curve fits of $\theta$ vs. $a_r$ for Ficoll according to the two-pore model were obtained using the parameters listed in Table 2 (Lo-ANP) and Table 4 (Hi-ANP).

The fractional fluid flow through the large pores (large-pore volume flow/GFR) was markedly increased, nearly 10-fold at 15 min, in Hi-ANP and then remained elevated compared with SHAM-60 even at 30 min ($P < 0.05$). For Lo-ANP, the fractional volume flow through the large pores was seen to be increased (more than doubled) at 5 ($P < 0.05$) and 15 min ($P < 0.05$), but not thereafter. The fractional hydraulic conductance accounted for by the large pores ($\theta_L$) increased almost three-fold in Hi-ANP at 5 and 15 min compared with SHAM-60 ($P < 0.01$), clearly indicating the formation of more large pores in the glomerular filter during infusion of high doses of ANP. Furthermore, there was an increase in $r_L$ in Hi-ANP at 5 and 15 min. In Lo-ANP, such an increment was actually significant at all time points ($P < 0.05$) except at 30 min.

**DISCUSSION**

This is the first direct assessment of the dynamics of glomerular permeability alterations occurring during infusions of ANP in the rat. The essential result of the study is that both low (34) and high ANP concentrations caused a rapid (within 5 min), partially reversible increase in glomerular permeability. This was followed by a very moderate, sustained increase in barrier permeability, which was significant for the high ANP dose. Even though the second, more sustained increase in permeability did not reach statistical significance in Lo-ANP
Table 3. Two-pore parameters, Lo-ANP

<table>
<thead>
<tr>
<th></th>
<th>SHAM 60 min</th>
<th>5 min</th>
<th>15 min</th>
<th>30 min</th>
<th>60 min</th>
<th>120 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-pore radius ($r_s$), Å</td>
<td>45.96 (45.66–46.29)</td>
<td>46.02 (45.79–46.18)</td>
<td>45.94 (45.81–46.31)</td>
<td>45.79 (45.28–45.86)</td>
<td>45.61 (45.27–45.77)</td>
<td>45.73 (45.73–45.73)</td>
</tr>
<tr>
<td>Large-pore radius ($r_L$), Å</td>
<td>122.36 (116.59–128.37)</td>
<td>192.78† (150.74–205.44)</td>
<td>183.03† (163.79–203.59)</td>
<td>108.63 (103.24–139.54)</td>
<td>146.11* (134.45–161.86)</td>
<td>159.74† (158.10–164.49)</td>
</tr>
<tr>
<td>$a_0 \times 10^5$</td>
<td>4.31 (3.21–5.66)</td>
<td>5.81 (3.86–12.1)</td>
<td>5.69 (2.98–7.77)</td>
<td>3.34 (2.61–5.04)</td>
<td>2.64* (2.10–3.4)</td>
<td>2.05* (2.01–2.10)</td>
</tr>
<tr>
<td>$J_vL/GFR$</td>
<td>6.87 (6.05–8.85)</td>
<td>22.5* (13.54–68.57)</td>
<td>18.61* (10.3–26.5)</td>
<td>8.05 (6.09–16.9)</td>
<td>8.13 (6.63–9.94)</td>
<td>6.67 (6.54–6.62)</td>
</tr>
<tr>
<td>$A_0/X$, cm/g</td>
<td>3.95 (3.70–4.84)</td>
<td>3.67 (2.93–4.13)</td>
<td>4.59 (2.84–5.76)</td>
<td>3.21 (2.66–4.94)</td>
<td>4.14 (2.98–4.55)</td>
<td>3.98 (3.61–5.95)</td>
</tr>
</tbody>
</table>

Median values are given together with ranges (1st–4th quartile); $n =$ no. of rats. $a_0$, Fractional ultrafiltration coefficient accounted for by large pores; $J_vL/GFR$, fractional fluid flow through large pores; $A_0/X$, effective pore area over unit diffusion path length. Statistical difference between SHAM and experimental groups: *$P < 0.05$, †$P < 0.01$, ‡$P < 0.001$.

Table 4. Two-pore parameters, Hi-ANP

<table>
<thead>
<tr>
<th></th>
<th>SHAM 60 min</th>
<th>5 min</th>
<th>15 min</th>
<th>30 min</th>
<th>60 min</th>
<th>120 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-pore radius ($r_s$), Å</td>
<td>45.96 (45.66–46.29)</td>
<td>46.40 (46.37–46.61)</td>
<td>46.84 (46.58–47.07)</td>
<td>46.56 (46.47–46.97)</td>
<td>46.24 (46.12–46.78)</td>
<td>46.35 (46.02–46.46)</td>
</tr>
<tr>
<td>Large-pore radius ($r_L$), Å</td>
<td>122.36 (116.59–128.37)</td>
<td>146.66† (140.01–163.02)</td>
<td>154.72† (135.55–172.12)</td>
<td>128.94 (113.59–141.78)</td>
<td>131.06 (124.10–139.85)</td>
<td>125.78 (128.39–131.78)</td>
</tr>
<tr>
<td>$a_0 \times 10^5$</td>
<td>4.31 (3.21–5.66)</td>
<td>18.10† (9.97–34.07)</td>
<td>18.48† (7.96–30.49)</td>
<td>4.69 (3.38–10.4)</td>
<td>6.28 (5.13–8.11)</td>
<td>7.96* (6.26–13.5)</td>
</tr>
<tr>
<td>$J_vL/GFR$</td>
<td>6.87 (6.05–8.85)</td>
<td>50.11 (29.3–114.2)</td>
<td>58.31 (23.8–102.3)</td>
<td>14.3* (9.39–29.5)</td>
<td>18.31 (14.5–22.1)</td>
<td>22.61 (17.7–38.3)</td>
</tr>
<tr>
<td>$A_0/X$, cm/g</td>
<td>3.95 (3.70–4.84)</td>
<td>3.39 (3.12–4.19)</td>
<td>3.30 (3.07–4.21)</td>
<td>2.94 (2.48–4.20)</td>
<td>3.18 (3.35–4.13)</td>
<td>3.86 (3.57–5.12)</td>
</tr>
</tbody>
</table>

Median values are given together with ranges (1st–4th quartile); $n =$ no. of rats. Statistical difference between SHAM and experimental groups: *$P < 0.05$, †$P < 0.01$, ‡$P < 0.001$. 
Rho-kinase inhibitor, influencing the contractile F-actin cytoskeleton in podocytes and endothelial cells. Even though previous studies from this group have indicated that the ultimate sieving barrier to proteins is not at the podocyte slit diaphragm (19, 27), podocyte interactions with the rest of the glomerular filtration barrier seem crucial for its integrity. It is thus speculated that the rapid alterations in glomerular permeability observed in this study may actually be a consequence of actions on podocyte actin dynamics. Endothelial cells may also be involved, in a way similar to how they react to, for example, histamine, substance P, or thrombin, or in anaphylaxis in nonfenestrated endothelium (20, 26). The first permeability peak induced by ANP actually showed a time cycle which is similar to that following massive histamine release in anaphylactic shock (0–30 min) (8).

On podocytes there are ANP binding receptors, which have been localized mostly to the foot processes (32). ANP receptors signal through a family of particulate guanylate cyclases (pGC) (18), which can induce cGMP formation in a dose-dependent fashion (3). The functional consequences of increases in cGMP in podocytes are, however, poorly understood. In undifferentiated rat podocytes, 1 μM ANP (3 × 10^6 ng/ml) produced a decreased intensity of F-actin fluorescence and rearrangements of actin in sparse, parallel bundles (31). This suggests that ANP might produce podocyte relaxation (31). It is thus speculated that such changes in the F-actin cytoskeleton may alter the shape of the podocytes, and hence, the tension they exert on the glomerular basement membrane, thereby affecting glomerular permeability.

In the present study, the Hi-ANP animals showed a clear-cut second steady-state phase of increased glomerular permeability, but in the Lo-ANP group this phase was less evident. However, Lo-ANP animals still seemed to have been moderately affected by ANP over 2 h, because the r_L had actually increased significantly at both 60 (P < 0.05) and 120 min (P < 0.01) in this group. Therefore, also low concentrations of ANP seemed to have produced sustained alterations in glomerular size selectivity, which may partly explain the microproteinuria occurring in states of plasma volume expansion.

In Hi-ANP (800 ng·kg⁻¹·min⁻¹ of ANP infusion), there was a marked fall in systemic MAP, but despite that, there was a well-maintained GFR. ANP has been shown to be able to stimulate unmyelinated vagal receptors in the myocardium to produce a marked fall in systemic MAP, but despite that, there was a noticeable reduction in GFR but this was completely prevented in the Hi-ANP group. The functional consequences of in-creases in cGMP in podocytes are, however, poorly understood. In undifferentiated rat podocytes, 1 μM ANP (3 × 10^6 ng/ml) produced a decreased intensity of F-actin fluorescence and rearrangements of actin in sparse, parallel bundles (31). This suggests that ANP might produce podocyte relaxation (31). It is thus speculated that such changes in the F-actin cytoskeleton may alter the shape of the podocytes, and hence, the tension they exert on the glomerular basement membrane, thereby affecting glomerular permeability.

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In conclusion, the present study, especially designed to assess 0 for albumin, because of unexpectedly high levels of free iodine and denatured protein in the radiolabeled albumin preparation (135I-albumin) at our disposal. Especially, the high concentrations of free label yielded abnormally high 0 values in tissue uptake studies under control (SHAM) conditions. However, we have previously demonstrated a near-perfect coupling between alterations in 0 for high-molecular-weight Ficoll and 0 for radiolabeled albumin under conditions of increased permeability (6, 8, 28). Thus, given the high correlation between 0 for albumin and 0 for Ficoll, we considered it quite safe in this study to rely upon the glomerular sieving of high-molecular-weight Ficoll as an indicator of glomerular permeability.

ACKNOWLEDGMENTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

REFERENCES


