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Dynamics of glomerular ultrafiltration: VI. Studies in the primate

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Dynamics of glomerular ultrafiltration: VI. Studies in the primate. Pressures and flows were measured in accessible surface glomeruli of the squirrel monkey under conditions of normal hydropenia. Mean glomerular capillary hydrostatic pressure and the mean glomerular transcapillary hydrostatic pressure difference ($\overline{\Delta P}$) averaged approximately 45 mm Hg and 35 mm Hg, respectively. These findings are in close accord with recent direct estimates in the rat. The net driving force for ultrafiltration was found to decline from a maximum value of about 12 mm Hg at the afferent end of the glomerular capillary network essentially to zero by the efferent end, indicating that, in the monkey as in the rat, filtration pressure equilibrium is achieved under normal hydropenic conditions. The monkey differs from the rat in one important respect, however, in that, as has long been recognized, the monkey tends to have higher systemic total plasma protein concentrations (C_A) than the rat. This is of interest since monkey, like man, is found to have lower filtration fractions than the rat. Since $\overline{\Delta P}$ is found to be essentially similar in monkey and rat, and since, at filtration pressure equilibrium, filtration fraction is determined by $\overline{\Delta P}$ and C_A, these observed differences in filtration fraction between rodent and primate must therefore be due to these differences in C_A.

Dynamique de l'ultrafiltration glomérulaire: VI. Etudes chez le primate. Les pressions et les débits ont été mesurés dans les glomérules superficiels accessibles du sagouin dans des conditions d'hydropénie physiologique. La pression hydrostatique capillaire glomérulaire moyenne et la différence de pression hydrostatique transcapillaire glomérulaire ($\overline{\Delta P}$) sont approximativement de 45 mm Hg et 35 mm Hg, respectivement. Ces constatations sont en accord étroit avec les mesures directes récentes chez le rat. La force motrice nette de l'ultrafiltration décroît d'une valeur maximum de 12 mm Hg à l'extrémité afférente du réseau capillaire glomérulaire à pratiquement zéro à l'extrémité éfférente, ce qui indique, chez le sagouin comme chez le rat, que l'équilibre de pression de filtration est obtenu dans les conditions d'hydropénie normale. Le sagouin diffère du rat à un égard important, cependant, en ce qu'il tend à avoir une concentration systémique plus élevée de protéines plasmatiques (C_A), ainsi que cela est connu de longue date. Ce fait est important dans le mesure où chez le sagouin, comme chez l'homme, des fractions de filtration plus faibles que celle du rat ont été obtenues. Du fait que des valeurs très semblables de $\overline{\Delta P}$ ont été obtenues chez le sagouin et le rat et puisqu'à l'équilibre de pression de filtration la fraction filtrée est déterminée par $\overline{\Delta P}$ et C_A les différences observées dans les fractions de filtration entre rongeurs et primates doivent donc être liées à ces différences de C_A.

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The availability of a unique strain of Wistar rats with surface glomeruli, together with technological advances that permit direct assessment of glomerular transcapillary pressures and flows, has recently enabled workers in this laboratory to gain considerable insight into the dynamics of glomerular ultrafiltration in this mammalian species [1–5]. In cortical glomeruli in the rat,[1] mean glomerular capillary hydrostatic pressure ($\bar{P}_{GC}$) and the net driving force for ultrafiltration ($\bar{P}_{UF}$) have been found to be considerably lower than estimates derived from previous indirect measurements [6–9].

Whether these values observed in rats are typical of glomerular pressures in larger mammals and primates is unknown. The present study was undertaken to examine this question directly, making use of the recent observation that kidneys of squirrel monkeys also possess surface glomeruli accessible to micropuncture [10]. The results indicate that the pressures in the glomerular capillary network of this primate are remarkably similar to those in the rodent.

[1] A limited number of direct measurements of $\bar{P}_{GC}$ made in capillaries of randomly encountered surface glomeruli in Sprague-Dawley rats by Daugharty, Ueki and Brenner (unpublished observations) have yielded values quantitatively similar to those obtained in the mutant Wistar strain.

Methods

Glossary of symbols

$\overline{AP}$	Mean femoral arterial pressure, *mm Hg*
C	Protein concentration, *g/100 ml*
EABF	Efferent arteriolar blood flow, *nl/min*
GBF, GPF	Glomerular blood flow and plasma flow, respectively, *nl/min*
GFR	Whole kidney glomerular filtration rate, *ml/min*
Hct_A	Blood hematocrit in femoral artery or afferent arteriole
k	Effective hydraulic permeability, *equation* 14, *nl/(sec·mm Hg·cm²)*
K_f	Ultrafiltration coefficient, *equation* 14, *nl/(sec·mm Hg)*
KW	Kidney weight, *g*
P	Hydrostatic pressure, *mm Hg*
P_{UF}	Net ultrafiltration pressure, *equations* 9, 10, 14, *mm Hg*
ΔP	Transmembrane hydrostatic pressure difference, $P_{GC}-P_T$, *mm Hg*
π	Colloid osmotic pressure, *mm Hg*
$\Delta\pi$	Transmembrane osmotic pressure difference, $\pi_{GC}-\pi_T$, *mm Hg*
R	Resistance to blood flow, *dynes·sec·cm⁻⁵*
R_{TA}	Total arteriolar resistance, R_A+R_E, *dynes·sec·cm⁻⁵*
S	Surface area available for ultrafiltration, *cm²*
SNFF	Single nephron filtration fraction
SNGFR	Single nephron glomerular filtration rate, *nl/min*
$(TF/P)_{IN}$	Tubule fluid to plasma inulin concentration ratio
V_{TF}	Tubule fluid flow rate, *nl/min*

Superscripts

——	Mean value

Subscripts

A	Afferent arteriole
C	Peritubular capillary
E	Efferent arteriole
GC	Glomerular capillary
T	Proximal tubule
TF	Tubule fluid
UF	Ultrafiltration

General. Studies were performed on nine male squirrel monkeys (*Saimiri sciureus*) weighing 472 to 824 g. All monkeys were allowed free access to water and were fed a balanced diet of commercial dry monkey chow (Purina) supplemented with fresh fruit. They were deprived of food but not water for 18 to 24 hours prior to study to reduce the volume of abdominal contents at the time of micropuncture.

Animals were anesthetized initially with an intramuscular injection of 25 mg of ketamine HCl (Vetalar, Parke, Davis and Co., Detroit, Michigan) followed by intravenous injection of 10 mg of sodium thiamylal (Surital, Parke, Davis and Co.). Small supplemental doses of the latter were given as needed. Each animal was placed on a temperature-regulated micropuncture table, and a tracheostomy was performed. Indwelling polyethylene catheters were inserted into the external jugular veins for infusion of inulin and fluids and into the left femoral artery for periodic blood sampling and estimation of mean arterial pressure ($\overline{AP}$). The left kidney was exposed through a midline incision, gently dissected free of its perirenal attachments and placed on a 1.5 cm^2 flat plastic (Lucite) holder. The ventral surface of the renal capsule was removed and the exposed renal surface was bathed continuously with isotonic NaCl heated to 37°C. A short polyethylene catheter was inserted into the left ureter for collection of urine.

Beginning approximately 45 min prior to micropuncture, monkeys were given a priming infusion of 2 ml of 10% inulin in isotonic NaCl followed by a continuous sustaining infusion at the rate of 4.5 to 6.0 ml/hour. This resulted in final plasma inulin concentrations of approximately 75 to 100 mg/100 ml. Using controlled suction techniques [11], three to five exactly timed (1 to 2 min) total collections of fluid were obtained from surface proximal tubules for determination of volume flow rate (V_{TF}) and inulin concentration, thereby permitting calculation of single nephron glomerular filtration rate (SNGFR). In four animals, two to four collections of urine were obtained from the left kidney for determination of flow rate, inulin concentration and whole kidney glomerular filtration rate (GFR). Concurrently, two to three samples of femoral arterial blood were obtained for measurement of hematocrit and plasma inulin and protein concentrations. The concentrations of these substances are considered to be equal to their concentrations in afferent arteriolar plasma (C_A). In addition, samples of blood from surface efferent arterioles were obtained for determination of efferent arteriolar protein concentration (C_E). $\overline{AP}$ was monitored throughout each study with an electronic pressure transducer (model P23AA, Statham Instruments, Inc., Los Angeles, California) attached to a direct-writing recorder (model 7702B, Hewlett Packard Co., Palo Alto, California). Mean hydrostatic pressures within single capillaries of surface glomeruli ($\bar{P}_{GC}$), efferent arterioles (P_E), second- and third-order peritubular capillaries (P_C) and proximal tubules (P_T) were measured with continuous recording, electronic servo-null micropipette transducers [12, 13]. For these measurements 2 M NaCl-containing micropipettes with outer tip diameters of 1 to 2 μm were used. Hydraulic output from the servo system was coupled electronically to a second channel of the Hewlett-Packard recorder by means of a pressure transducer (model P23Db, Statham Instruments, Inc., Los Angeles, California). Accuracy, frequency response and stability features of this servo system have been described in detail previously [13].

Analytical. The volume of fluid collected from indi-

vidual proximal tubules was determined from the length of the fluid column in a constant bore capillary tube of known internal diameter. The concentration of inulin in tubule fluid was measured, usually in duplicate, by the microfluorescence method of Vurek and Pegram [14]. Inulin concentration in plasma and urine was determined by the macroanthrone method of Führ, Kaczmarczyk and Krüttgen [15]. Protein concentration in efferent arteriolar (C_E) and femoral arterial (C_A) blood plasma was determined, usually in duplicate, with an ultramicrocolorimeter[2] using a recently described microadaptation [16] of the method of Lowry et al [17].

Calculations. Single nephron glomerular filtration rate:

$$SNGFR = (TF/P)_{IN} \cdot V_{TF}, \quad [1]$$

where $(TF/P)_{IN}$ and V_{TF} refer to the tubule fluid to plasma inulin concentration ratio and tubule fluid flow rate, respectively.

Single nephron filtration fraction:

$$SNFF = 1 - \frac{C_A}{C_E} \quad [2]$$

where C_A and C_E denote afferent and efferent arteriolar plasma protein concentrations, respectively.

Initial glomerular plasma flow rate:

$$GPF = \frac{SNGFR}{SNFF}. \quad [3]$$

Initial glomerular blood flow rate:

$$GBF = \frac{GPF}{1 - Hct_A}, \quad [4]$$

where Hct_A, the hematocrit of afferent arteriolar blood, is taken as being equal to femoral arterial hematocrit.

Efferent arteriolar blood flow rate:

$$EABF = GBF - SNGFR. \quad [5]$$

Resistance per single afferent arteriole:

$$R_A = \frac{\overline{AP} - \bar{P}_{GC}}{GBF} \times (7.962 \times 10^{10}), \quad [6]$$

where the factor 7.962×10^{10} is used to give resistance in units of dynes·sec·cm^{-5} when $\overline{AP}$ and $\bar{P}_{GC}$ are expressed in mm Hg and GBF, in nl/min.

Resistance per single efferent arteriole:

$$R_E = \frac{\bar{P}_{GC} - P_C}{EABF} \times (7.962 \times 10^{10}). \quad [7]$$

Total arteriolar resistance for a single pre- to postglomerular vascular unit:

$$R_{TA} = R_A + R_E. \quad [8]$$

[2] Designed and constructed by Dr. Gerald Vurek, Laboratory of Technical Development, National Heart and Lung Institute, Bethesda, Maryland.

Estimates of the net ultrafiltration pressure (P_{UF}) at the afferent = (P_{UF_A}) and efferent-most (P_{UF_E}) portions of the glomerular capillary:

$$P_{UF_A} = \bar{P}_{GC} - P_T - \pi_A \quad [9]$$

$$P_{UF_E} = \bar{P}_{GC} - P_T - \pi_E, \quad [10]$$

where π_A and π_E, afferent and efferent arteriolar colloid osmotic pressures, were calculated from femoral arterial and efferent arteriolar plasma protein concentrations using the Landis-Pappenheimer equation[3] [18]. *Equations* 9 and 10 contain the assumption that the colloid osmotic pressure of fluid in Bowman's space (π_T) is negligible. This assumption has been validated by the finding in four monkeys that the protein concentration of fluid in Bowman's space is less than 200 mg/100 ml. Accordingly, π_T is well below 1 mm Hg.

Mean glomerular transcapillary hydrostatic pressure difference:

$$\overline{\Delta P} = \bar{P}_{GC} - P_T. \quad [11]$$

Results

Table 1 summarizes individual and mean values for several measures of nephron and microvascular function. Values for $\overline{AP}$ and whole kidney GFR are also shown. $\overline{AP}$ averaged 115 mm Hg ± 3.5 SEM, with individual values ranging from 96 to 140 mm Hg. GFR, measured in four animals, averaged 1.45 ml/min ± 0.2. Variations in GFR less than as shown in Table 1 are obtained when these values are corrected for variations in kidney weight (KW). This correction results in values of 0.69, 0.72, 0.61 and 0.66 ml/(min·g of KW) for animals 5 through 8, respectively (the only animals in which both GFR and KW were available). These values agree closely with results reported by others [10, 19, 20]. $\bar{P}_{GC}$ measured in 15 surface glomeruli of nine animals ranged from 41.4 to 52 mm Hg and averaged 48.5 mm Hg ± 1.5. These values are similar to values for normal hydropenic rats previously reported [1–3, 5]. The ratio $\bar{P}_{GC}/\overline{AP}$ averaged 0.43. P_T averaged 12.6 mm Hg ± 0.6. The mean transcapillary hydrostatic pressure difference, $\overline{\Delta P}$ (*equation* 11), was uniform from animal to animal, averaging 35.9 mm Hg ± 1.3, a value in close accord with that reported for the rat [1–3, 5]. P_E and P_C averaged 14.2 mm Hg ± 1.3 and 9.3 ± 0.5, respectively. The pressure drop along surface afferent arterioles

[3] This equation assumes that the ratio of albumin to globulin in plasma is roughly 1.0. Electrophoretic analysis of plasma from four monkeys in the present study yielded ratios approximating unity in each case (mean = 0.95 ± 0.08).

Table 1. Summary of the measured determinants of glomerular ultrafiltration in nine squirrel monkeys

Animal No.	Body weight, g	Kidney weight, g	$\overline{AP}$, mm Hg	$\bar{P}_{GC}$, mm Hg	P_T, mm Hg	P_C, mm Hg	C_A, g/100 ml	C_E, g/100 ml	π_A, mm Hg	π_E, mm Hg	SNGFR, nl/min	SNFF	GPF, nl/min	GFR, ml/min
1				41.4	13.7		6.1	9.1			13.3			
				42.1	11.1		6.5	8.2			14.2			
				43.6	12.9			8.8			19.6			
					11.1						17.2			
											15.0			
	Mean,	741	—	120	42.4	12.1	8.9	6.3	8.7	21.8	36.3	15.9	0.28	56.7	—
2					42.8	11.1	7.4	7.2	9.5			15.7			
					42.1	10.3	8.1	7.2	9.8			17.0			
					42.8	12.9	8.1					16.8			
						9.6						14.1			
	Mean,	600	—	112	42.6	11.0	7.9	7.2	9.6	26.8	43.2	15.9	0.25	62.7	—
3						11.1		6.1	8.1			18.4			
						14.0		5.9	8.7			11.2			
												11.5			
	Mean,	625	1.6	96	51.7	12.6	7.4	6.0	8.4	20.3	34.3	13.7	0.28	42.8	—
4					56.0	11.0		7.7	9.2			25.1			
					49.0	13.0		7.7	9.1			23.1			
					48.0							30.2			
	Mean,	821	3.3	118	51.0	12.0	9.5	7.7	9.1	29.8	39.5	26.1	0.16	166.5	—
5						15.5		6.1	8.0			27.5			
						15.5		6.5	7.2			36.4			
												31.2			
	Mean,	670	2.6	112	48.0	15.5	10.3	6.3	7.6	21.8	29.2	31.7	0.17	185.3	1.80
6						14.0			8.6			11.6			
						14.0			8.6			11.6			
												12.7			
												13.3			
	Mean,	824	2.3	140	51.7	14.0	9.6	6.9	8.6	25.1	35.6	12.3	0.20	62.0	1.66
7						16.2	12.6	6.0				14.6			
						12.6	11.8	6.0				18.0			
												13.5			
												12.2			
	Mean,	524	1.7	100	53.2	14.4	12.2	6.0	7.8	20.3	30.4	14.6	0.23	63.2	1.01
8								7.7	9.3			7.6			
								7.5	10.4			9.8			
												10.6			
												8.5			
	Mean,	590	2.0	130	51.5	11.0	7.5	7.6	9.8	29.2	44.4	9.1	0.22	40.4	1.32
9						10.0									
						12.0									
	Mean,	472	—	105	44.5	11.0	10.0	—	—	—	—	—	—	—	—
Total															
	mean	652	2.2	115	48.5	12.6	9.3	6.8	8.7	24.4	36.6	17.4	0.22	85.6	1.45
	SEM	41	0.3	3	1.4	0.6	0.5	0.2	0.3	1.4	1.9	2.7	0.02	20.0	0.2
	N (animals)	9	6	9	9	9	9	8	8	8	8	8	8	8	4

($\overline{AP} - \bar{P}_{GC}$) averaged 66 mm Hg ± 5, compared with a uniformly smaller pressure drop averaging 39 ± 1 ($P < 0.001$) along surface efferent arterioles ($\bar{P}_{GC} - P_C$). Fig. 1 illustrates the average drop in blood pressure at various sites along the renal microcirculation in the monkey (*dashed line*), normalized to the mean aortic pressure. Also shown is the pressure profile of the mutant Wistar rat (*solid line*), based on mean data reported previously [1–3, 5]. Remarkable quantitative agreement between species is evident. Calculations of absolute resistance to blood flow through single afferent (R_A) and efferent (R_E) arterioles (*equations* 6 and 7) yield mean values of 4.5×10^{10} dynes·sec·cm^{-5} ± 0.8 and 3.1×10^{10} ± 0.5, respectively, indicating that, on the average, afferent arterioles contribute some 60% of the total resistance to blood flow to the level of the smallest accessible peritubular capillaries. These values for R_A and R_E are essentially the same as values reported for the rat [2, 3, 5].

Measurements of C_A and C_E in eight animals yielded values averaging 6.8 g/100 ml ± 0.2 and 8.7 ± 0.3, respectively. Although this value for C_E is typical of that found in the rat [1–3, 5, 16], the mean value of C_A obtained for the monkey exceeds by nearly 1.0 g/100 ml that generally found in the rat. This high value of C_A in primates, including man, has been demonstrated repeatedly [20–24]. π_A and π_E calculated from these values of C_A and C_E are shown in Table 1. As given in *equations* 9 and 10, the measurements in the present study allow determination of the magnitude of

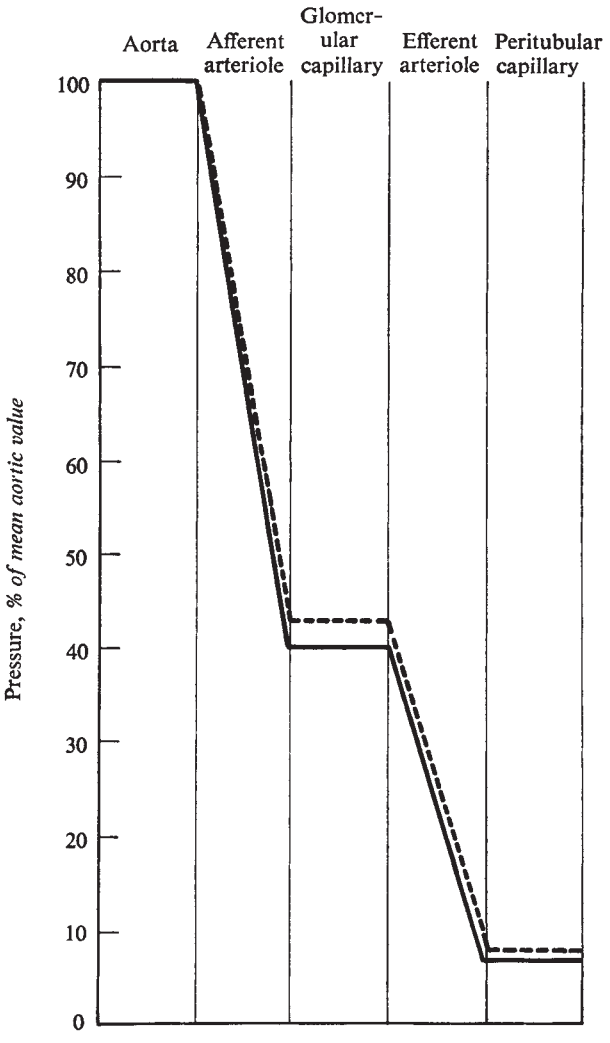

Fig. 1 *Profiles of mean pressures along the renal microcirculation, normalized to the mean aortic pressure, in the monkey* (dashed line) *and rat* (solid line). Data used for constructing the *solid line* have been reported previously [1–3, 5].

the glomerular transcapillary pressure difference favoring ultrafiltration at afferent (P_{UF_A}) and efferent (P_{UF_E}) ends of the capillary network in each animal. On the average, P_{UF_A} attained a value of 12.4 mm Hg $\pm$ 1.9. By the efferent end of the network, this imbalance of pressures favoring ultrafiltration essentially disappeared, P_{UF_E} averaging -0.4 ± 2.3. Although this average value for P_{UF_E} did not differ significantly from zero ($P > 0.5$), calculation of values for P_{UF_E} from data in Table 1 shows not inconsiderable variations from monkey to monkey. This variability, considerably greater than that found previously in the rat [1–5], is the result, we think, of the greater technical difficulties inherent in performing these measurements in the monkey, due to the greater degree of pulsatile motion of the kidney in this species. In view of the finding that the values for P_{UF_E} are distributed randomly about zero, however, the overall findings are taken to suggest that filtration pressure equilibrium is very likely achieved in the normal hydropenic monkey, in accord with recent findings in the rat [1–5].

Individual and mean values for SNGFR are given in Table 1. It can be seen that although there was relatively little scatter among values in individual animals, the variations in mean values from animal to animal often were considerable. SNFF was generally found to be lower in the monkey than in the rat [1–3, 5, 11, 16], averaging 0.22 ± 0.02. These low values for cortical filtration fraction coincide closely, however, with similarly low values for whole kidney filtration fraction reported by others for primates, including man [25–31]. Values for GPF, calculated for individual animals using *equation* 3, are also given in Table 1. As with values for SNGFR, considerable variation in GPF was noted from animal to animal. This variation could not be accounted for by systematic variations in $\overline{AP}$, $\overline{\Delta P}$, C_A, body weight, state of hydration, duration of study or dosage of anesthetic. To some extent, the higher values of GPF observed in animals numbered 4 and 5 correlate with the higher kidney weights in these animals. Irrespective of the cause of these higher values of GPF, however, it is evident from Table 1 that these high values of GPF were associated with correspondingly high values of SNGFR.

Discussion

In accordance with recent observations from this laboratory in the rat [1–5], the present study in the squirrel monkey demonstrates that the formation of glomerular ultrafiltrate occurs coincident with a progressively diminishing imbalance of pressures across the glomerular capillary wall. During the normal hydropenic conditions of the present study, this imbalance averaged approximately 12 mm Hg at the afferent end of the glomerular capillary network and fell essentially to zero by the efferent end. This fall in net ultrafiltration pressure along the capillary is due primarily to the progressive increase in plasma oncotic pressure (reflecting the largely protein-free nature of the ultrafiltrate) and not to any large fall in P_{GC}, the local value of glomerular capillary hydrostatic pressure. The decline in P_{GC} along the glomerular capillary, the axial pressure drop, is inferred to be quite small. The sites at which P_{GC} is measured are not identified but are presumed to be randomly distributed along the glomerular capillaries. π_E is (to good approximation) a lower bound on ΔP, so that if there were a substantial axial pressure drop, the measured value of ΔP would

be expected, on average, to exceed π_E. The finding of filtration pressure equilibrium therefore indicates that the axial pressure drop is quite small compared to ΔP. The available anatomical and rheological data are not sufficient to allow a very precise estimate of the axial pressure drop, but calculation of the Poisseuille pressure drop for a tube with dimensions and flow rates similar to those expected for glomerular capillaries, using the viscosity of whole blood, suggests that the axial pressure drop need not be more than 1 to 2 mm Hg. This same conclusion has recently been found to apply to the rat [2].

The principal finding in this study is that the measured determinants of glomerular ultrafiltration in the monkey are quantitatively similar to those measured in the rat using identical techniques. Essentially the same values of $\bar{P}_{GC}$ and $\overline{\Delta P}$ exist in these two species, and on average, filtration pressure equilibrium exists during hydropenic conditions. Of interest, however, is the finding that filtration fractions are lower in the monkey than in the rat, a finding true not only for surface nephrons (this study) but for the kidney as a whole [25, 26]. The explanation for this difference between species is readily evident from the results of the present study. *Equation* 2 may be rewritten, thus:

$$SNFF \cong 1 - \frac{\pi_A}{\pi_E}. \qquad [12]$$

The equality in *equation* 12 is only approximate because of the nonlinear relationship between π and C [18, 32]. At filtration pressure equilibrium, $\pi_E = \overline{\Delta P}$, which gives rise to the following equation:

$$SNFF \cong 1 - \frac{\pi_A}{\overline{\Delta P}}. \qquad [13]$$

From *equation* 13 it is evident that, at equilibrium, filtration fraction is determined by π_A (or C_A) and $\overline{\Delta P}$. Since $\overline{\Delta P}$ was found to be the same in monkey and rat [1–3, 5], and since equilibrium obtains in both species, the observed differences in filtration fraction between species must be due to differences in C_A. Indeed, the mean value of C_A in the present study exceeded that typically measured in the rat [1–5, 16, 32] by approximately 1 g/100 ml.

The dependence of filtration fraction on C_A is illustrated graphically in Fig. 2. The *solid curves* in this figure show π_E as a function of filtration fraction, each curve corresponding to a different assumed value of C_A (over the range from 4 to 8 g/100 ml). Values for π_E at each filtration fraction were computed using the Landis-Pappenheimer equation [18]. The *dashed line* corresponds to the approximate mean value of $\overline{\Delta P}$ measured in monkey and rat [1–3, 5]. The intersection between a given curve and the dashed line, therefore,

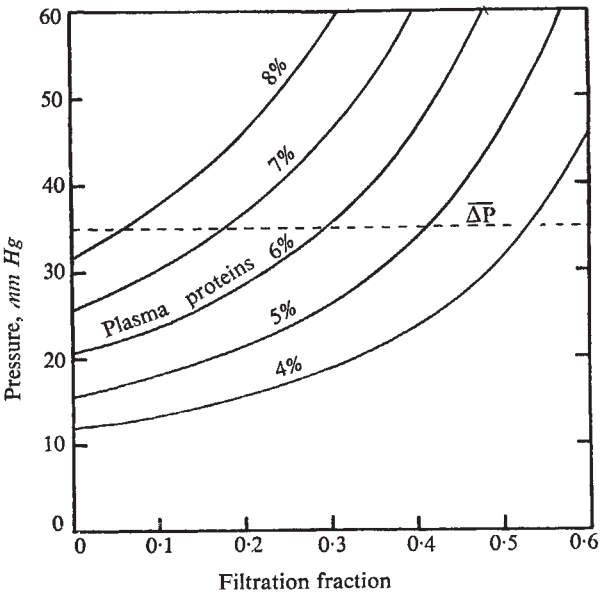

Fig. 2 *The dependence of filtration fraction on systemic plasma protein concentration (C_A), assuming filtration pressure equilibrium and a value for the mean glomerular transcapillary hydrostatic pressure difference ($\overline{\Delta P}$) of 35 mm Hg.* The *curved lines* denote values for π_E computed from C_A for given values of filtration fraction, using the equation of Landis and Pappenheimer [18]. This figure is a modification of an earlier figure by Landis and Pappenheimer [18].

yields the filtration fraction, at equilibrium, for the corresponding value of C_A. Thus, for the monkey, where C_A typically averages about 7 g/100 ml, filtration fraction averages about 0.2, in accordance with the findings in this and other studies [25, 26]. For the rat, where C_A typically averages 6 g/100 ml, filtration fraction according to the figure should average about 0.3, again in close accordance with values measured in normal hydropenic rats [1–3, 5, 11, 16]. It is interesting to note that in man, C_A and whole kidney filtration fraction are very similar to values in the monkey, namely 7 g/100 ml and 0.2, respectively [22–24, 27–31]. From Fig. 2, it is clear that if filtration pressure equilibrium obtains in man, the value of $\overline{\Delta P}$ for man must also be some 35 mm Hg.

The rate of glomerular ultrafiltration may be expressed as

$$SNGFR = K_f \cdot \bar{P}_{UF} = k \cdot S \cdot (\overline{\Delta P} - \overline{\Delta \pi}), \qquad [14]$$

where $\bar{P}_{UF}$ is the mean driving pressure (P_{UF} averaged along the length of the capillary), and K_f, the ultrafiltration coefficient, is the product of effective hydraulic permeability of the capillary wall (k) and capillary surface area (S). $\overline{\Delta \pi}$ is the mean transcapillary colloid osmotic pressure difference. If $\bar{P}_{UF}$ could be evaluated from the measured pressures, *equation* 14 would permit calculation of K_f from values

of $\bar{P}_{UF}$ and SNGFR. A unique value of $\bar{P}_{UF}$, and thus K_f, can only be obtained, however, under disequilibrium conditions (where $\pi_E < \overline{\Delta P}$) [4, 33]. Attempts were made in four animals in the present study to produce disequilibrium by expanding plasma volume and raising GPF to extremely high levels, a maneuver found to be successful in producing disequilibrium in the rat [4]. Unlike the rat, however, this degree of plasma volume expansion in the monkey produced such marked increases in kidney pulsations as to preclude precise micropuncture manipulations. Although lacking a unique K_f value for the monkey, we have determined, using a recently described mathematical model of glomerular ultrafiltration [33], that the value of K_f obtained at disequilibrium in the rat, 0.08 nl/(sec·mm Hg) [4], is sufficiently large to yield filtration pressure equilibrium in the monkey under the conditions of the present study. Indeed, it is entirely possible that K_f for the monkey is even larger than the value obtained in the rat, since $K_f = k \cdot S$ (*equation* 14) and since capillary surface area for the primate has been reported to be some two to four times that of the rat [34, 35].

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