Renal disease pathophysiology and treatment: contributions from the rat

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ABSTRACT
The rat has classically been the species of choice for pharmacological studies and disease modeling, providing a source of high-quality physiological data on cardiovascular and renal pathophysiology over many decades. Recent developments in genome engineering now allow us to capitalize on the wealth of knowledge acquired over the last century. Here, we review rat models of hypertension, diabetic nephropathy, and acute and chronic kidney disease. These models have made important contributions to our understanding of renal diseases and have revealed key genes, such as Ace and P2rx7, involved in renal pathogenic processes. By targeting these genes of interest, researchers are gaining a better understanding of the etiology of renal pathologies, with the promised potential of slowing disease progression or even reversing the damage caused. Some, but not all, of these target genes have proved to be of clinical relevance. However, it is now possible to generate more sophisticated and appropriate disease models in the rat, which can recapitulate key aspects of human renal pathology. These advances will ultimately be used to identify new treatments and therapeutic targets of much greater clinical relevance.

KEY WORDS: Rat, Chronic kidney disease, Diabetic nephropathy, Genetically modified rats, End-organ damage, Renal transplantation

Introduction
The prevalence of chronic kidney disease (CKD) is estimated to be 8-16% worldwide (Jha et al., 2013; Stevens et al., 2007). With an aging population, and rising levels of hypertension, diabetes and obesity, renal diseases pose an increasing burden on public healthcare. Two million people worldwide are currently on renal replacement therapy (RRT), dialysis or have a renal transplant. However, this figure makes up only ~10% of all individuals who actually need RRT, with a greater number dying due to the inadequate availability of therapies (https://www.kidney.org/kidneydisease/global-facts-about-kidney-disease#_ENREF_3) and skewed treatment towards affluent countries with access to healthcare (Jha et al., 2013). Furthermore, kidney disease represents an independent risk factor for cardiovascular mortality (Tonelli et al., 2006). Individuals often present with complex renal pathologies resulting from numerous insults, both genetic and environmental. The interactions of combined metabolic and cardiovascular factors make it difficult to identify individuals who will benefit most from available treatments to slow or prevent disease progression (Jha et al., 2013). It is therefore imperative that we develop new strategies to identify those at high risk of progressive kidney disease and to discover new therapies to slow the rate of disease progression in these individuals. Animal models can provide insight into the pathophysiology of kidney disease and can be used to test novel therapies. However, their utility is limited by how well they recapitulate the key features and mechanisms of progressive human disease. Although it can be argued that rodents are poor replacements for humans in studies of kidney disease (Becker and Hewitson, 2013), much valuable information about the underlying etiology of renal disease has been revealed by studying rat models.

The functional unit of the kidney is the nephron (see Glossary, Box 1), which is closely integrated with the renal blood supply (Fig. 1). The human kidney filters 180 liters of plasma through its glomeruli, and produces 1 to 2 liters of urine daily. Approximately 99% of filtered sodium is retrieved as it passes through various sections of the nephron before reaching the collecting duct.

Acute kidney injury (AKI) occurs when there is a rapid decline in glomerular filtration rate (GFR; see Glossary, Box 1), usually accompanied by impaired microcirculation, inflammation and/or tubular injury or necrosis and reduced renal blood flow (Basle et al., 2012). AKI is initiated by various clinical insults, including hypotensive shock, sepsis, surgery or the administration of nephrotoxic agents such as cisplatin (Tanaka et al., 2005) and contrast agents (commonly used for medical imaging) (Mehrman and Nikolsky, 2006). Following mild kidney injury, an adaptive repair response might ensue, leading to kidney regeneration. However, with more severe injury, regeneration is incomplete and nephron mass can be replaced by scar tissue, leading to CKD (Bucaloiu et al., 2012; Chawla et al., 2011). There are limited treatment options available for AKI, and its associated mortality remains high (Ferenbach and Bonventre, 2015). AKI can be induced in rats by performing ischemia-reperfusion surgery or by administering toxins such as cisplatin. However, these single insults are unlikely to fully recapitulate the multiple injurious processes that have typically occurred in individuals with AKI.

CKD is an umbrella term for any renal disease that results in the progressive loss of kidney function over time. The kidney possesses only a limited capacity for regeneration, and repeated or sustained injury to the kidney results in maladaptive responses (Ferenbach and Bonventre, 2015), including the deposition of excess extracellular matrix (ECM; see Glossary, Box 1), particularly collagen, in the glomerulus and tubulointerstitium of the kidney (Fig. 2). The pathological changes associated with CKD include glomerulosclerosis and tubulointerstitial fibrosis (see Glossary, Box 1), which result in the loss of normal renal architecture, microvascular capillary rarefaction (see Glossary, Box 1), hypoxia and tubulatryrophy. These changes lead to the loss of renal filtrative...
capacity and ultimately to end-stage renal disease. Many rodent models mimic features of early CKD; however, only few exhibit features of end-stage renal disease (ESRD).

The substantial wealth of physiological knowledge available for the rat makes it the species of choice for modeling aspects of kidney disease and for exploring therapeutic strategies \textit{in vivo}. For several decades, the mouse has been the pre-eminent mammalian organism for disease modeling because of its genetic tractability. With recent developments in genome engineering, the rat is rapidly catching up.

In this Review, we discuss how rat models have contributed to our understanding of renal pathophysiology and hold promise for developing improved treatments to halt the progression of CKD or to repair kidney damage in humans. We consider aspects of hypertensive renal damage, diabetic nephritis, AKI and CKD. We emphasize the utility and limitations of the rat in recapitulating features of human renal pathologies \textit{in vivo} and how this model organism has shed light on complex underlying mechanisms of disease progression of therapeutic relevance – information that might ultimately lead to the development of new drug treatments and targets (Aitman et al., 2016, 2008).

**Models of hypertensive renal damage**

In up to 95% of individuals with hypertension, no specific underlying genetic cause for the condition is identified despite contributory factors such as smoking or obesity. However, in a small proportion of cases, hypertension is secondary to endocrine or renal disease. Sustained exposure to high blood pressure adversely affects cardiac, brain, vascular and renal tissues, making hypertension a major cause of end-organ damage (see Glossary; Box 1). Hence, renal disease might be both a cause and consequence of hypertension, forming a vicious circle whereby hypertension causes kidney damage, which then exacerbates the high blood pressure. Hypertensive glomerulosclerosis is characterized by arterial wall thickening, loss of renal autoregulation, glomerulosclerosis, tubular atrophy and interstitial fibrosis (Hill, 2008). Arterial stiffening due to increased pulse pressure affects autoregulation of the afferent arterioles, and leads to progressive glomerular hypertrophy and damage with atrophy of the attached tubule. Reduced glomerular filtration causes compensatory...
hyperfiltration in other glomeruli, leading to glomerulosclerosis (which also results from ischemic damage) and ultimately to tubular damage and fibrotic lesions of the interstitial cells (Hill, 2008).

Classically, genetic animal models of high blood pressure, such as the spontaneously hypertensive rat (SHR) and the related salt-loaded stroke-prone (SHRSP) rat, generated by protracted rounds of breeding and selection for high blood pressure (see also Table 1), have been used to study the effects of chronic hypertension (Okamoto and Aoki, 1963; Okamoto et al., 1964; Pravenec and Křen, 2005). It has been proposed that the pathological progression of hypertensive damage to kidney damage in this rat model mirrors that seen in human hypertension (Hultström, 2012), with renal damage resulting from altered pressure-dependent autoregulation of renal blood flow.

The underlying mutations and their homeostatic sequelae, which contribute to hypertension and to multi-end-organ damage in the SHR, seem to be very complex. Renal microarray has identified >200 genes that differ more than fourfold in their levels of expression between adult SHRs or SHR substrains (Watanabe et al., 2015) and Wistar Kyoto control rats. The availability of the entire SHR genome sequence (Atanur et al., 2010) provides an opportunity to identify potentially causative polymorphisms in these genes. Undoubtedly, strains such as the SHR have helped to confirm the involvement of multiple genes in hypertension and kidney damage. However, identifying which mutations are primary and which are secondary to the disease remains an unresolved question for cardiovascular research.

Transgenesis allows researchers to investigate the biological consequence(s) of a genetic perturbation. However, elucidating the homeostatic effects of altered gene function is not always straightforward, as exemplified by the mRen2 rat (Mullins et al., 1990), which overexpresses the mouse renin (Ren2) gene, causing severe hypertension (see Table 1). Renin is a key component of the renin-angiotensin aldosterone system (RAAS; see Glossary, Box 1), the activation of which increases levels of circulating angiotensin II (AngII), and causes systemic vasoconstriction and sodium resorption in the kidney in order to increase blood pressure. Both kidney and plasma levels of renin are low in the mRen2 rat (Bachmann et al., 1992) making this a low-renin hypertension model. Hypertension was attenuated with captopril, which inhibits the RAAS component angiotensin-converting enzyme (Ace), indicating AngII dependence (Bader et al., 1992). High levels of mouse-transgene-derived inactive renin, and low levels of active renin, were produced in the adrenal gland, indicating that tissue
RAAS is responsible for hypertension in this model (Peters et al., 1993). The crossing of the renin transgene onto a closely related outbred Sprague Dawley strain generated animals that developed malignant hypertension and end-organ damage by 8 weeks of age (see Glossary, Box 1) (Whitworth et al., 1994). In particular, the kidney exhibited glomerulosclerosis and interstitial fibrotic lesions. When the mRen2 transgene was crossed onto the inbred Fischer (F344) and Lewis rat strains, the resulting consomic strains (see Glossary, Box 1) were susceptible and resistant to malignant hypertension, respectively. Genome-wide screening and quantitative trait analysis identified two modifier loci on chromosomes 10 and 17, which contributed to malignant hypertension susceptibility (Kantachuvesiri et al., 1999). The mRen2 rat strains have been studied extensively for over 25 years, under both hypertensive and hyperglycemic conditions.

In a more refined model, the Cyp1a1Ren2 rat (Kantachuvesiri et al., 2001), expression of the mRen2 gene is under the control of an inducible promoter in the inbred Fischer strain. This allows the researcher to control the degree of AngII-dependent hypertension and consequent end-organ damage, its speed of attainment and, also, to look at repair processes, once the inducer (indole-3-carbinol; I-3-C) is withdrawn (see 'Models of diabetic nephropathy' below). The earliest hypertension-induced renal injury identified in the Cyp1a1Ren2.Fischer strain is limited to the preglomerular vasculature (Ashek et al., 2012). The later-onset hypertensive kidney damage includes arterial wall thickening, glomerulosclerosis and interstitial fibrosis similar to the renal damage caused by hypertension in humans. Increases in urinary albumin and angiotensinogen were observed with malignant hypertension (Milani et al., 2010), although the latter did not reflect changes in angiotensinogen gene expression in the kidney cortex (Prieto et al., 2011). Proteinuria was alleviated in this model by antagonism of the mineralocorticoid receptor (MR; see Glossary, Box 1) with spironolactone (Ortiz et al., 2007). After the transient induction of hypertension, Cyp1a1Ren2 rats developed salt-sensitive hypertensive renal damage,

![Pathophysiological processes linked to kidney disease](image)

Fig. 2. The pathophysiological processes linked to kidney disease. (A) A normal, healthy kidney (left), and a magnified view of the structure of a tubule and its associated vasculature (right). (B) A chronically diseased kidney, showing the processes that lead to tubulointerstitial fibrosis. (C,D) Histological sections of an adult rat kidney, stained with Masson's trichrome (20× magnification; scale bars: 50 µm). (C) The glomerular and tubular architecture of a normal adult rat kidney, and (D) glomerulosclerosis (#) and tubulointerstitial fibrosis (*) in a 12-month-old hydroxysteroid dehydrogenase 2 (Hsd11b2)-knockout rat exhibiting end-stage renal disease.
<table>
<thead>
<tr>
<th>Rat model</th>
<th>Strain</th>
<th>Type of model</th>
<th>Phenotype</th>
<th>Strengths of model</th>
<th>Limitations of model</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypertensive kidney damage</td>
<td>Spontaneously</td>
<td>Inbred</td>
<td>Genetic: multiple mutations</td>
<td>Observe focal segmental glomerulosclerosis (FSGS) typical of human hypertensive nephropathology</td>
<td>Complicated genetics and phenotype</td>
<td>Pravenec and Kren, 2005; Okamoto et al., 1964</td>
</tr>
<tr>
<td>mRen2</td>
<td>Sprague Dawley/</td>
<td>Genetic: mouse Ren2 transgene</td>
<td>Fulminant (severe) hypertension*; end-organ damage</td>
<td>Observe hyperplastic arteriosclerosis typical of human malignant hypertension (MH)</td>
<td>Early mortality due to MH (8-10 weeks)</td>
<td>Mullins et al., 1990</td>
</tr>
<tr>
<td>Cyp1a1mRen2 (F344)</td>
<td>Inbred F344</td>
<td>Genetic: mouse Ren2 transgene under Cyp1a1 promoter; inducible with indole-3-carbanol (I-3-C)</td>
<td>Inducible hypertension; susceptible to MH*</td>
<td>Control severity of hypertension; facilitates study of renal or vascular repair</td>
<td>Genetic background must be considered</td>
<td>Kantachuvesiri et al., 2001</td>
</tr>
<tr>
<td>Cyp1a1mRen2 (Lew)</td>
<td>Inbred Lewis (Lew)</td>
<td>Genetic: mouse Ren2 transgene under Cyp1a1 promoter; inducible with I-3-C</td>
<td>Inducible hypertension; resistant to MH</td>
<td>As in cell above; facilitates study of renal protection</td>
<td>Genetic background must be considered when comparing with F344 model</td>
<td>Liu et al., 2009</td>
</tr>
<tr>
<td>Hsd2KO</td>
<td>Inbred F344</td>
<td>Genetic: global Hsd11b2 knockout</td>
<td>Syndrome of apparent mineralocorticoid excess (SAME); salt-sensitive (SS) hypertension*</td>
<td>Hypertensive from young age (~5 weeks)</td>
<td>SAME is a rare disease in humans; complicated response to gene knockout</td>
<td>Mullins et al., 2015</td>
</tr>
<tr>
<td>Dahl salt-sensitive (SS) rat</td>
<td>Inbred</td>
<td>Genetic: multiple mutations</td>
<td>SS hypertension</td>
<td>Highly reproducible substrains: SS versus salt-resistant (SR) control</td>
<td>Complicated genetics and phenotype</td>
<td>Hu et al., 2014; Dahl et al., 1962</td>
</tr>
<tr>
<td>Two-kidney, one clip (2K1C) model</td>
<td>Various</td>
<td>Surgical</td>
<td>Hypertension; nephropathy of contralateral kidney</td>
<td>Clipped kidney acts as internal control, although an untreated control kidney should also be included</td>
<td>Variable phenotype between labs</td>
<td>Finne et al., 2014; Goldblatt et al., 1934; Okamura et al., 1986</td>
</tr>
<tr>
<td>Diabetic nephropathy (DN)</td>
<td>mRen2/STZ</td>
<td>Genetic: mouse Ren2 transgene; pharmacological: DN induced with STZ</td>
<td>Hypertension and diabetes*</td>
<td>Some features of human DN, including glomerulosclerosis, tubulointerstitial fibrosis, arteriolal hyalinosis, reduced glomerular filtration rate</td>
<td>Early mortality due to MH (8-10 weeks); renal injury might be due to hypertension not diabetes</td>
<td>Kelly et al., 1998</td>
</tr>
<tr>
<td>Cyp1a1mRen2</td>
<td>Inbred F344</td>
<td>Genetic: mouse Ren2 transgene under Cyp1a1 promoter; inducible with I-3-C and STZ</td>
<td>Inducible hypertension and diabetes*</td>
<td>Mimics pathology and renal transcriptomic changes in human DN</td>
<td>No arteriolar hyalinosis or advanced kidney failure</td>
<td>Conway et al., 2012; Conway et al., 2014</td>
</tr>
<tr>
<td>Acute kidney injury (AKI)</td>
<td>Nephrotoxicity</td>
<td>Pharmacological: e.g. cisplatin or contrast agent</td>
<td>Acute tubular necrosis (ATN)</td>
<td>Ease of induction of tubular injury</td>
<td>Uncommon causes of ATN in humans</td>
<td>Mehran and Nikolsky, 2006; Tanaka et al., 2005</td>
</tr>
<tr>
<td>Ischemia-reperfusion injury (IRI)</td>
<td>Various</td>
<td>Surgical</td>
<td>ATN</td>
<td>Straightforward surgery; severity of tubular injury can be controlled by altering duration of ischemia</td>
<td>Human ATN usually multifactorial</td>
<td>Conger et al., 1991; Schrimpf et al., 2014; Kramann and Humphreys, 2014</td>
</tr>
<tr>
<td>Renal fibrosis</td>
<td>Unilateral ureteral obstruction (UOO)</td>
<td>Surgical</td>
<td>Inflammation and fibrosis; obstructive uropathy</td>
<td>Simple and rapid model of fibrosis; mirrors features of human congenital UOO; useful as a screening tool for anti-fibrotics</td>
<td>Adult human kidney does not fibrose as quickly during obstruction</td>
<td>Terashima et al., 2010</td>
</tr>
</tbody>
</table>
hypothesis, which could be attenuated by the superoxide dismutase mimetic tempol, implicating the superoxide anion in the development of salt-sensitive hypertension (Howard et al., 2005).

The \textit{Cyp1a1Ren2} transgene is carried on the Y chromosome and, by crossing the inducible Fischer male to a Lewis female, followed by selective backcrossing of the F1 progeny to Lewis or Fischer animals, congenic lines (see Glossary, Box 1) were derived. These lines retain the transgene and either susceptibility or resistance to end-organ damage, on an otherwise resistant or susceptible background (Kantachuvesiri et al., 1999). Whole-renal, microarray-based, gene-expression profiling studies of the parental and congenic strains revealed genes in the congenic region that were differentially expressed between the parental and congenic background (Kantachuvesiri et al., 1999). Whole-renal, microarray-based, gene-expression profiling studies of the parental and congenic strains revealed genes in the congenic region that were differentially expressed between the parental and congenic background (Kantachuvesiri et al., 1999).

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Rat model & Strain & Type of model & Phenotype & Strengths of model & Limitations of model & References \\
\hline
\textbf{Chronic kidney disease (CKD)} & Inbred & Genetic: human diphertheria toxin transgene & Podocyte loss; focal segmental glomerulosclerosis (FSGS) & Develops nephrotic range proteinuria, podocyte loss, FSGS & Artificial mechanism of injury: podocyte loss rapid and simultaneous & Wharram et al., 2005 \\
\textit{AA-4E-BP1} & Inbred & Genetic: \textit{AA-4E-BP1}$^2$ transgene driven by podicin promoter & Mechanical failure of podocytes; proteinuria; FSGS & – & Artificial mechanism of injury & Fukuda et al., 2012a \\
Passive Heymann nephritis (PHN) & Sprague Dawley & Pharmacological: anti-Fx1A antibody & PHN; membranous nephropathy & Develop immune deposits and proteinuria & Antibody in human disease is directed against phospholipase A2 receptor & Salant et al., 1979 \\
Anti-Thy 1.1 & Various & Pharmacological: IgA nephropathy & Mesangio-proliferative glomerulonephritis (MPGN) & Has several features of the human clinical pathology, e.g. mesangial proliferation, glomerular ECM deposition & Self-limiting disease course in rat, limited tubular involvement and minimal renal functional change & Nazeer et al., 2009; Denby et al., 2011 \\
5/6th nephrectomy & Various & Surgical & Reduced nephron number; reduced glomerular filtration rate (GFR) & Can exhibit progressive decline in renal function (strain specific) and increase in blood pressure & Difficult surgery; high mortality & Gilbert et al., 2012 \\
Nephotoxic nephritis (NTN) & Various & Pharmacological: nephotoxic globulin & Immune-complex-mediated glomerular nephritis; proteinuria; P2RX7 increase & Develops proteinuria and some histopathological changes that are observed in human disease & Batch-to-batch variation in disease severity & Turner et al., 2007; Taylor et al., 2009 \\
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\end{tabular}
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\textsuperscript{UK Home Office regulations for animal research do not allow end-stage renal failure (ESRF) or malignant hypertension (MH) as end point of experiment.}

\textsuperscript{\textit{AA-4E-BP1}, eukaryotic translation initiation factor binding protein 1 (\textit{EIF4EBP1}), a member of the mammalian target of rapamycin complex 1 pathway.}

\textsuperscript{STZ, streptozotocin.}
in hypertension and renal disease. Clinical trials of P2X7 antagonists in the treatment of inflammatory diseases have shown limited therapeutic benefit to date (Bartlett et al., 2014). Given the large number of splice variants (Cheewatrakoolpong et al., 2005) and disease-related single-nucleotide polymorphisms (SNPs) (Jiang et al., 2013) in the human P2RX7 gene, a productive future research strategy could be the selective humanization of rats to develop tissue-specific or disease-relevant therapeutic strategies.

In the two-kidney, one clip (2K1C) hypertensive system (Goldblatt et al., 1934), which has been implemented in rats, a clip on the left renal artery activates the RAAS system. Although both kidneys are exposed to an equivalent increase in AngII, only the non-clippered kidney shows hypertensive damage (Cervenka et al., 1999). Recently, the non-clippered kidney was found to have increased mRNA, protein and urinary levels of angiotensinogen, suggesting that kidney damage occurs through increased AngII, and that angiotensinogen could be used as an early biomarker of kidney damage (Shao et al., 2016). Exposure of the non-clippered kidney to increased AngII was ameliorated by nitric oxide (NO) release, suggesting that this is a protective mechanism (Helle et al., 2008).

Additional early hypertension-induced changes in the renal tubules were identified by micro-dissection of visibly undamaged tubulointerstitial tissue from the non-clippered kidney. Proteomic analysis using mass spectrometry revealed the differential expression of over 300 proteins compared to control samples, with profibrotic Rho-signaling proteins being the most highly overrepresented (Finne et al., 2016). Such studies should help to identify additional biomarkers of early tubule damage, which in time could be used diagnostically. It should be noted, however, that the clipped kidney is not physiologically equivalent to an untreated (sham) control kidney; thus, the latter should always be included as a control when comparing clipped and non-clippered kidneys (Palm et al., 2008, 2010).

Despite complexities of the SHR, SHRSP and 2K1C hypertension models, a recent gene-expression profiling study revealed a common progression in hypertensive renal damage (Skogstrand et al., 2015). Of the 88 genes similarly regulated in all three models, 40 were also identified in gene-expression profiles from human fibrotic kidneys. This suggests that pathogenic pathways underlying kidney damage are conserved between rats and humans.

Hypertensive models generated by genetic modification
Gene-knockout technology has only recently become available for the rat with the isolation of rat embryonic stem (ES) cells (see Glossary, Box 1) (Buehr et al., 2008; Li et al., 2008), which can be used as a tool for gene modification. The genetic tractability of the rat has also been greatly facilitated by genome-engineering technologies, such as zinc-finger nucleases (ZFNs) (Geurts et al., 2009), transcription activator-like effector nucleases (TALENs) (Tesson et al., 2011) and the CRISPR-Cas9 system (see Glossary, Box 1) (Li et al., 2013). Genome endonuclease technologies generate a sequence-specific DNA double-strand break, which is repaired by error-prone, non-homologous end-joining. Any insertions or deletions introduced at the target site cause missense or nonsense mutations. The PhysGen knockout program (http://pga.mcw.edu/) has utilized these technologies to generate a wide variety of knockout rat models in genes associated with cardiovascular or renal disease. One of the earliest ZFN-knockout rat models generated with a clear renal phenotype was the hypotensive renin-knockout rat (Moreno et al., 2011). Disruption of the renin gene caused profound disruption to normal kidney development. The inner renal medulla was morphologically rudimentary and there were signs of cortical interstitial fibrosis. These changes could be related to the concomitant reduction in AngII production, and support the assertion that the RAAS is essential for normal kidney development in mammals (Guron and Friebig, 2000).

Another rat knockout model that exhibits reduced renin levels is the Hsd2KO rat (Mullins et al., 2015). The enzyme 11β-hydroxysteroid dehydrogenase type 2 (Hsd11b2) protects the MR from inappropriate activation by cortisol (corticosterone), in the kidney principal cell, by inactivating it to cortisone (11-dehydrocorticosterone). In this model, ZFN-induced knockout of the Hsd11b2 gene causes inappropriate activation of the MR, leading to salt-sensitive hypertension, suppression of renin secretion, and hypokalemia (see Glossary, Box 1). This phenotype closely models the human syndrome of apparent mineralocorticoid excess (SAME). The rats exhibit severe renal injury, including protein casts and atrophic tubules, segmental glomerulosclerosis, tubule-interstitial fibrosis and proteinuria (Mullins et al., 2015). These are all features associated with chronic exposure to hypertension and with MR activation seen in human kidney disease (Ueda and Nagase, 2014). Interestingly, the Hsd2KO rat model demonstrates metabolic protection, including increased insulin sensitivity and reduced mesenteric fat accumulation, due to the depletion of the substrate for Hsd11b1 in adipose tissue. This suggests that treatment with MR inhibitors might reverse the adverse cardiovascular effects of SAME (which include hypokalemia, hypertension, proteinuria and end-organ damage), while promoting the beneficial metabolic effects of Hsd11b2 inactivation (Mullins et al., 2015).

Salt-sensitive hypertension involves a complex feedback loop of salt appetite and sodium retention. Hsd11b2 in the murine brain triggers a central drive to consume salt (Evans et al., 2016). The rat Hsd2KO model offers a more robust platform to investigate the physiological mechanisms of central versus renal-centric salt sensitivity than is feasible in the mouse. Decreasing dietary salt consumption might reduce the burden of CKD in humans (McMahon et al., 2013). Intriguingly, an alternative, albeit more invasive, strategy to ameliorate salt-sensitive hypertension has been recently demonstrated. Renal medullary dysfunction in salt-sensitive Dahl rats (Dahl et al., 1962) was found to reflect a reduction in adult (CD133+) mesenchymal stem cells (MSCs) in the medulla. Injection of MSCs, but not of renal medullary interstitial cells, into the renal medulla attenuated immune-cell infiltration and sodium retention, and reduced systemic blood pressure (Hu et al., 2014). The rationale for using MSCs stems from numerous animal studies, which have demonstrated that these cells have protective effects in acute and chronic kidney injury models (Fleig and Humphreys, 2014; Wang et al., 2013).

The co-injection of single-strand oligonucleotides with ZFNs, TALENs or CRISPR-Cas9 components can be used to introduce targeted SNPs or to repair mutations, through homology-driven repair (HDR). Rapid improvements in CRISPR-Cas9 technology, using donor plasmids as HDR templates, have included the introduction of fluorescent reporters (Ma et al., 2014a), the one-step generation of a floxed allele (loxP sites flanking an exon) (Ma et al., 2014b) and conditional knockout using Cre-recombinase rat strains (see Glossary, Box 1) (Ma et al., 2014a). Recently, Wistar-Kyoto rats and SHRs that ubiquitously express GFP have been produced, using the Sleeping Beauty transposon system. These strains will prove useful for investigating cell fate and transplantation in the hypertensive kidney (Garcia Diaz et al., 2016).

The identification of genes such as Ace, P2rx7 and Hsd11b2, or specific genetic variants or splice variants of genes, that seem to
play key roles in moderating hypertensive damage, renal pathology and salt-sensitivity has the potential to enable future identification of individuals at risk of hypertensive kidney damage based on their genetic profile. With the availability of humanized transgenic models, Cre-loxP technology, reporter strains, gene knockouts and knock-ins, and the ability to correct candidate genes in mutant rat strains, many of the tools available to the mouse community are now available in the rat. Although the inherent problem of off-target events remain for genome-engineering technologies, targeting in rat ES cells and screening for clones free of off-target events remains a possibility. Thus, many more-refined and increasingly sophisticated rat models, which more closely recapitulate human renal pathology caused by hypertensive damage, can be expected in the future, and might help to predict targeted therapeutic response more faithfully.

Models of diabetic nephropathy

Diabetic nephropathy (DN; see Glossary, Box 1) is the single most common cause of end-stage kidney disease in the western world (Saran et al., 2015). The use of reliable animal models of DN could greatly facilitate research by providing mechanistic insights into this disease to help identify novel therapeutic targets. These in turn could provide a platform for preclinical testing of such novel therapies. Unfortunately, one of the roadblocks to DN research is the lack of preclinical models that recapitulate important functional, structural and molecular pathological features of progressive human diabetic kidney disease. Although several rodent models of type 1 diabetes [streptozotocin (STZ)-induced (Cooper et al., 1988)] and type 2 diabetes [Zucker, Goto Kakizaki (Jansen et al., 2003)] have been employed to study DN (see Glossary, Box 1), these models fail to recapitulate all of the hallmarks of this disease as defined by the Diabetic Complications Consortium (DiAComp; https://www.diacomp.org/shared/validationcriteria.aspx). The inability of animal models to fully replicate human DN might explain why many therapies that have been beneficial in preclinical models of this disease have proven to be ineffective in clinical trials. For example, direct renin inhibitors were beneficial in reducing proteinuria in rodent models (Kelly et al., 2007). However, the absence of progressive renal failure in these models meant that the efficacy of these inhibitors in reducing renal function could not be tested. Human studies confirmed a beneficial effect of direct renin inhibitors on reducing proteinuria (Parving et al., 2008) but, importantly, they did not slow the rate of renal-function decline (Parving et al., 2012). Furthermore, the increased risk of hyperkalemia (see Glossary, Box 1) resulting from treatment with direct renin inhibitors in patients with impaired renal function (Parving et al., 2012) was not highlighted in the rodent models, where blood potassium levels remained normal.

Although hyperglycemia (see Glossary, Box 1) is a pre-requisite for the development of DN, hemodynamic factors play a substantial role in the progression of this disease. Individuals with advanced DN invariably have hypertension, and tight control of blood pressure is as important as glycemic control in slowing disease progression (Mogensen, 1998). Hypertension might not only be a consequence of nephropathy but a key driver of kidney disease in diabetes. Indeed, subtle abnormalities in blood pressure, such as loss of nocturnal dipping (see Glossary, Box 1), precede the onset of albuminuria (see Glossary, Box 1) in adolescents with type 1 diabetes (Lurbe et al., 2002). Furthermore, there are two case reports regarding individuals with longstanding diabetes, hypertension and unilateral renal artery stenosis (Berkman and Rifkin, 1973; Béroniade et al., 1987) whose conditions mimic the 2K1C rat model of hypertension. Autopsy findings in both cases revealed no pathological evidence of nephropathy in the kidney downstream of the arterial stenosis, despite severe nephropathy in the contralateral kidney. The implications of these findings are that unilateral renal artery stenosis might prevent the transmission of systemic hypertension to the kidney parenchyma and the subsequent development of nephropathy, even though both kidneys have been exposed to an equivalent degree of hyperglycemia and to increased AngII exposure. Thus, hyperglycemia or elevated angiotensin levels alone are insufficient to promote advanced DN; the development of hypertension is a prerequisite for disease progression. How hypertension interacts with hyperglycemia to promote nephropathy is unclear, but the application of cyclical stretch to mesangial cells cultured in high-glucose media increases the expression of pro-fibrotic genes, suggesting a role for increased mechanical strain (Gruden et al., 2000). In rat mesangial cells grown in high-glucose media, ATP and a P2X7 agonist dose-dependently increased albuminuria (see Glossary, Box 1) in adolescents with type 1 diabetes. Indeed, subtle abnormalities in blood pressure, such as loss of nocturnal dipping (see Glossary, Box 1), precede the onset of albuminuria (see Glossary, Box 1) in adolescents with type 1 diabetes (Lurbe et al., 2002). Furthermore, there are two case reports regarding individuals with longstanding diabetes, hypertension and unilateral renal artery stenosis (Berkman and Rifkin, 1973; Béroniade et al., 1987) whose conditions mimic the 2K1C rat model of hypertension. Autopsy findings in both cases revealed no pathological evidence of nephropathy in the kidney downstream of the arterial stenosis, despite severe nephropathy in the contralateral kidney. The implications of these findings are that unilateral renal artery stenosis might prevent the transmission of systemic hypertension to the kidney parenchyma and the subsequent development of nephropathy, even though both kidneys have been exposed to an equivalent degree of hyperglycemia and to increased AngII exposure. Thus, hyperglycemia or elevated angiotensin levels alone are insufficient to promote advanced DN; the development of hypertension is a prerequisite for disease progression. How hypertension interacts with hyperglycemia to promote nephropathy is unclear, but the application of cyclical stretch to mesangial cells cultured in high-glucose media increases the expression of pro-fibrotic genes, suggesting a role for increased mechanical strain (Gruden et al., 2000). In rat mesangial cells grown in high-glucose media, ATP and a P2X7 agonist dose-dependently increased albuminuria (see Glossary, Box 1) in adolescents with type 1 diabetes. Indeed, subtle abnormalities in blood pressure, such as loss of nocturnal dipping (see Glossary, Box 1), precede the onset of albuminuria (see Glossary, Box 1) in adolescents with type 1 diabetes (Lurbe et al., 2002). Furthermore, there are two case reports regarding individuals with longstanding diabetes, hypertension and unilateral renal artery stenosis (Berkman and Rifkin, 1973; Béroniade et al., 1987) whose conditions mimic the 2K1C rat model of hypertension. Autopsy findings in both cases revealed no
synergized to promote a 500-fold increase in albuminuria, and caused moderate glomerulosclerosis and tubulointerstitial fibrosis—all features of moderately advanced human DN. However, there was no significant decline in renal function in this model, and some key pathological features of DN, such as arteriolar hyalinosis (see Glossary, Box 1), were not observed.

Microarray and RNA-sequencing technologies provide a non-biased view of gene expression changes. Thus, comparing transcriptomic changes in DN patients with rat models of the disease might reveal common disease mechanisms, identify relevant biomarkers and therapeutic targets, and enable the rational selection of the rodent model that most closely recapitulates changes seen in DN kidneys. Up to 50% of genes that were differentially expressed in the tubulointerstitial compartment of the kidney in human DN (Lindemeyer et al., 2007) were also similarly up- or downregulated in the renal cortex of hyperglycemic and hypertensive Cyp1al1mRen2 rats (Conway et al., 2012). For example, one downregulated gene in both the rat model and in the kidneys of individuals with DN was epidermal growth factor (EGF). Urinary EGF levels reflect renal EGF expression, and subsequent studies confirmed that low levels of urinary EGF excretion predict a poor renal outcome in individuals with DN and with other CKDs (Betz et al., 2016; Tu et al., 2015). Hence, non-biased transcriptomic approaches could be used to identify as-yet-unknown prognostic biomarkers for therapeutic targets or to recruit high-risk individuals for clinical trials. Such transcriptomic datasets should be made freely available on databases such as Geodataset (http://www.ncbi.nlm.nih.gov/gds/) or Nephroseq (https://www.nephroseq.org), as this will enable researchers to select the model in which their pathway of interest is differentially activated in a similar manner to human disease. Such ‘precision modeling’ could improve the chances of translating findings made in rodent models to the clinic.

Although the natural history of DN is one of inexorable progression towards end-stage kidney disease, the tight control of blood glucose and blood pressure can lead to the regression of albuminuria in up to 50% of individuals with DN (Perkins et al., 2003). More remarkably, regression of established glomerulosclerosis and tubulointerstitial fibrosis has been observed in individuals with moderately advanced DN who achieve sustained normoglycemia after receiving a pancreas transplant (Fioretto et al., 1998, 2006), although this takes up to 10 years to become evident. The pathways that promote regression remain poorly understood, largely because serial biopsies are rarely performed in individuals who are responding to treatment.

Rodent models provide insights into mechanisms of injury, regeneration and repair. The Cyp1al1mRen2 rat model of DN is particularly useful in this regard because hypertension can be induced and then blood pressure normalized by adding and then removing dietary 1-3-C; inserting subcutaneous insulin implants can also control STZ-induced hyperglycemia. In one study, 28 weeks of hyperglycemia and hypertension (the injury phase) were followed by tight glycemic and blood pressure control for an additional 8 weeks (the reversal phase), resulting in the partial regression of albuminuria (Conway et al., 2014). Microarray analysis of the renal transcriptome during both the injury and reversal phases revealed ~650 genes that were upregulated during injury, almost 100 of which reverted to control levels following reversal of hyperglycemia and hypertension. This gene set was enriched for genes that encoded ECM proteins, fibroblast markers and acute-phase reactants, indicating that the tight control of glucose and blood pressure might suffice to switch off the formation of new scar tissue. This was supported by the finding that there was no further increase in the severity of glomerulosclerosis or tubulointerstitial fibrosis during the 8-week reversal phase. In addition, many genes of unknown function, which reverted to control levels during repair, might be implicated in the fibrotic- or acute-phase response and hence they merit further investigation. Conversely, almost 400 genes remained significantly upregulated despite the normalization of blood glucose and blood pressure. This gene set was enriched for genes that encoded proteins implicated in innate and adaptive immunity, in particular pro-resolution macrophages and regulatory T cells, suggesting that attempts at repair have been initiated. Although glomerulosclerosis and tubulointerstitial fibrosis did not reduce during the reversal phase, this was to be expected given the protracted period required for regression of fibrosis following pancreas transplantation in humans (Fioretto et al., 2006). Permanent or long-term upregulation of some of these genes might be responsible for the salt sensitivity observed in I-3-C-induced rats (Howard et al., 2005).

Bilateral renal denervation has emerged as a potential treatment for multiple-drug-resistant hypertension in individuals with bilateral single renal arteries, but results from recent clinical trials have questioned its efficacy for individuals with secondary (or accessory) renal arteries (Bhatt et al., 2014; Herling et al., 2016; Khan et al., 2014). When bilateral renal denervation was performed in the mRen2/STZ rat model, it reduced signs of renal pathology, albuminuria and the expression of fibrotic markers. This suggests that renal denervation might attenuate renal injury in DN (Yao et al., 2014), presumably with similar caveats regarding efficacy.

In summary, rat studies can mimic many of the features of human DN, including progressive proteinuria, key pathological features such as glomerulosclerosis and tubulointerstitial fibrosis, and the activation of many pathways that are implicated in human DN. However, none fully recapitulate human DN, with few exhibiting arteriolar hyalinosis and a progressive decline in renal function. Rat models have highlighted the benefits of Ace inhibitors and the prognostic value of EGF in the treatment of DN. A comparison of the results from microarray and RNA-sequencing technologies in rodent models and human DN will continue to identify new candidates for therapeutic interventions to prevent kidney damage or to enhance repair and regeneration.

Models of acute and chronic kidney disease
AKI affects multiple cell types in the kidney, including endothelial and tubular cells, which are adversely affected by hypoxia. It is not clear whether hypoxia (the reduction of tissue oxygen supply to below physiological levels) or re-oxygenation (increased exposure to oxygen, as seen with reperfusion following ischemia) causes AKI, but it is associated with altered intra-renal microcirculation and oxygenation (Rosenberger et al., 2006). Ischemia-reperfusion injury (IRI; see Glossary, Box 1) is extensively used as a model of AKI, but hypoxic damage predominantly affects proximal tubule segments in the outer stripe of the outer medulla and might not recapitulate human AKI, which often includes medullary oxygen insufficiency. Damage to the thick ascending limb is attenuated following IRI, probably because the reduced solute transport leads to improved oxygenation of the distal tubule (Rosenberger et al., 2006). Following acute IRI, the vascular function of rats remains impaired for several days (Conger et al., 1991). The pericyte (see Glossary, Box 1) detaches from the endothelium under pathological conditions, leading to microvascular rarefaction and hypoxia (Schrimpf et al., 2014). Pericytes might contribute to the pool of scar-forming myofibroblasts (see Glossary, Box 1) (Kramann and
Adults with diabetes and hypertension are at risk of developing chronic kidney disease (CKD), with rates of progression and development of end-stage renal disease (ESRD) being particularly high in these individuals. Autopsy studies of patients with diabetes, hypertension or both reveal a disproportionate number of regenerating tubules fail to re-establish normal tubule ultrastructure, which cause a selective reduction in medullary blood flow and tissue oxygenation, these could provide better models of AKI and could enable investigation of hypoxia-inducible factors, adaptive responses and potential therapies (Rosenberger et al., 2006). The development of rat models should enhance our understanding of AKI and help to design therapeutic strategies to block maladaptive responses.

Pre-existing CKD affects the severity of AKI in humans and their recovery (Liangos et al., 2006). This has been experimentally modeled in rats using the renal-mass-reduction model of CKD with an additional induced IRI. CKD develops in the 5/6th nephrectomy rat model (in which the 5/6th of renal mass is surgically ablated; see Table 1). When AKI is induced in this model via IRI, a disproportionate number of regenerating tubules fail to re-differentiate. This is associated with significant loss of tubular VEGF expression and with substantial capillary rarefaction. Defective tubules also have pro-fibrotic properties that increase tubulointerstitial fibrosis (Polichnowski et al., 2014). Further investigation of this model will provide a greater understanding at the molecular level of the AKI to CKD transition seen in humans.

Rat models of AKI and CKD have been used as a platform to test potential new therapies, including novel anti-fibrotic agents on key pro-fibrotic pathways (Terashima et al., 2010). Using transgenic rats carrying a luciferase reporter gene under the control of rat α1(I) collagen and rat α2(II) collagen, the anti-fibrotic effects of inhibiting TGFβ signaling (using a TGFβR1 inhibitor) and AngII signaling (using an AngII-receptor blocker (ARB), olmesartan) were examined (Terashima et al., 2010). This study revealed that ARBs had an anti-fibrotic effect, independent of hemodynamic effects, in the unilateral ureteral obstruction (UUO) model of rapid renal fibrosis (see Table 1), which induces a marked change in renal perfusion.

In a rat model of arteriolosclerotic nephropathy, the neutralization of TGFβ with anti-TGFβ antibody improved renal function and reduced acute tubular necrosis, interstitial inflammation, vascular rarefaction and myofibroblast accumulation (Pozdziek et al., 2016). The disruption of proximal tubule organelle ultrastructure was also prevented. However, these findings have not translated to the clinic; agents that block TGFβ and retard CKD have failed to improve renal function despite the promising preclinical results (Lee et al., 2015). These findings again support the observation that animal models typically recapitulate only part of the human condition – particularly CKD and its progression to ESRD. Animal models such as the UUO rat, used as a model of renal fibrosis, can be studied for a few weeks at most, whereas, in humans, these conditions usually develop over many years. Pathways that are important initially might not be as important in the pathophysiology of later disease and could explain the lack of translation of successful preclinical compounds.

Studies performed in various transgenic rat models have led to new insights into glomerulosclerosis, and in particular into the role of the podocyte (see Glossary, Box 1). A direct causative relationship exists between the degree of podocyte depletion and the development of proteinuria and glomerulosclerosis (Kim et al., 2001; Wharram et al., 2005). However, the mechanisms by which podocyte depletion can lead CKD to progress to end-stage kidney disease are poorly understood.

To examine the effect of podocyte depletion, the human diphtheria toxin receptor (hDTR) was specifically expressed in podocytes, generating the hDTR Fischer rat model (see Table 1), which has histopathological features commonly seen in the human disease focal segmental glomerulosclerosis (FSGS; see Glossary, Box 1), including mesangial expansion, segmental and global sclerosis (Wharram et al., 2005). These features occur in proportion to the degree of podocyte depletion. Although a return to normal glomerular architecture over time did not occur, once the glomerulus was destabilized by a critical degree of podocyte loss, the continuous infusion of an ACE inhibitor (enalapril) and ARB (losartan) was found sufficient to stabilize the glomeruli. The renoprotective effect of ARBs is not through blood pressure reduction alone and seems to be due to a direct effect on the podocyte (Fukuda et al., 2012b; Wharram et al., 2005).

Another transgenic Fischer rat model, this time expressing a dominant-negative phosphorylation site mutant of AA-4E-BP1, the eukaryotic translation initiation factor binding protein 1 (EIF4EBP1) transgene (see Table 1), has been used to examine the effect of growth on podocyte failure (Fukuda et al., 2012a). Driven by the podocin promoter, the EIF4EBP1 transgene encodes a member of the mammalian target of rapamycin complex 1 (mTORC1) pathway, which is a key determinant of the cellular hypertrophic response, driven by the podocin promoter. Transgenic AA-4E-BP1 rats have normal kidney histology with no proteinuria below 100 g body weight, but develop end-stage renal disease by 12 months. The observed proteinuria and glomerulosclerosis were linearly related to body weight increases and transgene dose. Histological observations revealed rare areas of glomerular basement membrane, where podocyte foot processes had pulled apart, and consequent adhesion to the Bowman capsule. In the AA-4E-BP1 model, it seems that proteinuria develops through mechanical failure of the podocyte epithelial layer. This mechanism of podocyte depletion is different from direct podocyte damage and death. It also provides a mechanistic explanation for a separate group of diseases that lead to global glomerulosclerosis or focal segmental glomerulosclerosis (see Glossary, Box 1) in childhood and obesity (Fukuda et al., 2012a), suggesting that limiting calorie intake could be beneficial in reducing the severity of the human condition. With additional developments, such as intravital imaging (Peti-Peterdi et al., 2016) and visualization of calcium dynamics (Szelenyi et al., 2015) to observe podocyte function glomerular injury processes in real time, a deeper understanding of the mechanisms that lead to the development of renal pathology should identify novel therapeutic targets.
Novel monoclonal rat models of glomerulosclerosis have also been generated, such as the TGR(ET-2)37 rat model, which expresses high levels of human endothelin-2 (ET2) in the kidney (Hocher et al., 1996). These rats develop blood-pressure-independent glomerulosclerosis, which demonstrates that the human ET2 gene can have a blood-pressure-independent, growth-promoting effect on the rat glomerulus.

Apoptosis is a key feature of the progression of CKD. Recently, ouabain, which is a cardiotonic steroid, has been found to have anti-apoptotic actions. Chronic ouabain treatment of rats with passive Heymann nephritis (PHN; a model of human membranous nephropathy, a slow progressive proteinuric kidney disease (Salant et al., 1979)] prevented the loss of podocytes, reduced the level of apoptotic proximal tubule cells and reduced renal fibrosis (Burlaka et al., 2016). Ouabain might represent a novel therapy that could potentially protect against apoptosis and prevent the loss of functional tissue in chronic proteinuric kidney disease.

The anti-Thy.1.1 model of glomerulonephritis is an experimental rat model that mimics human antigen-triggered, immune-induced mesangio-proliferative glomerulonephritis (MPGN; see Glossary, Box 1), such as IgA nephropathy. This well-characterized model of glomerular injury has been used to investigate molecular mechanisms of mesangial proliferation. Protecemic studies have revealed several proteins that show altered expression in this model (Nazeer et al., 2009), particularly the four and a half LIM domain protein 2 (FHL2), which increases mesangial cell proliferation in vitro (Lu et al., 2012) and could represent a new target for treating MPGN. This model has proven to be useful in identifying key stress-induced microRNAs, such as miR-21 and miR-214 (Denby et al., 2011), which are upregulated during renal injury. These microRNAs have since been found to be differentially expressed in human biopsies of individuals with IgA nephropathy, and their upregulation correlates linearly with renal fibrosis (Hennino et al., 2016), demonstrating the translational relevance of this model.

Other rat models of glomerulonephritis include the nephrotoxic nephritis (NTN) model (see Table 1), which established that levels of the P2X7 receptor protein are increased in the glomerulus. This correlates with increased glomerular P2X7 in human biopsy samples from patients with nephritis due to lupus (Turner et al., 2007). In the rat NTN model, the P2X7 antagonist A-438079 prevented antibody-mediated glomerulonephritis through reduced inflammatory damage due to a reduction in macrophage infiltration into the glomerulus (Taylor et al., 2009).

Rat models have proved to be invaluable in the field of regenerative cell therapy for renal disease. The potential of bone-marrow-derived MSCs to accelerate healing has been demonstrated in several rat models of hypertension (as discussed above) and of renal disease, including in the anti-Thy.1.1 model (Li et al., 2006), the 5/6th nephrectomy model of progressive CKD (Cavagneri et al., 2009; Choi et al., 2009) and in an AKI model induced by cisplatin (Urt-Filho et al., 2016). MSCs might reverse AKI by a paracrine mechanism rather than by MSC transdifferentiation. Intravenous injection of microvesicles, released from cultured human MSCs, inhibited tubular apoptosis and stimulated regeneration (Gatti et al., 2011). The renoprotective effect was lost if microvesicles were pre-treated with RNase, or if the pro-angiogenic microRNAs, miR-126 and miR-296, were depleted. This suggests that the miRNAs, delivered by microvesicles, are able to reprogram hypoxic resident renal cells (Cantaluppi et al., 2012). Importantly, MSCs taken from either the 5/6th nephrectomy model or the adenine-induced nephropathy model and transplanted into the anti-Thy.1.1 model failed to induce healing. Both CKD and uremia adversely affected transplanted MSCs, which exhibited cellular senescence (Klinkhammer et al., 2014). This result brings into question the use of autologous MSCs for the treatment of CKD.

In summary, AKI and CKD share a spectrum of renal pathologies. The identification of early biomarkers could allow the practitioner to harness adaptive repair and regenerative mechanisms, and prevent the maladaptive profibrotic pathways. A better understanding of the roles of, and of the potential cross-talk between, pericytes, myofibroblasts, tubular epithelium and podocytes is key to developing new therapies, and the rat is well placed to deliver such advances.

Renal transplantation
Renal transplantation was first performed in the rat over 50 years ago. Although the microsurgical techniques involved remain challenging, they are more readily mastered in rats than in mice. Several different combinations of inbred and outbred rat strains can be used to model various complications of renal transplantation, including IRI, acute rejection and chronic allograft nephropathy (CAN; see Glossary, Box 1) (Shrestha and Haylor, 2014). Renal transplantation from a Fischer donor to a Lewis recipient is the most common model of CAN in rats (White et al., 1969). Fisher and Lewis rat strains differ partially at the major histocompatibility loci (MHC) I and II, and this weak histocompatible combination results in CAN in rat in the absence of immunosuppression (Hancock et al., 1992; Paul et al., 1998). Ace inhibition can limit kidney damage in this transplant model (Noris et al., 2003), which has also been used to assess the development of alloimmunity (de Heer et al., 1994), the efficacy of immunosuppressants (Chandraker et al., 1998), non-immune therapies (Magee et al., 1999) and the development of fibrosis in the graft (Jain et al., 2000). The small molecule BB3 is a hepatocyte growth-factor mimetic, and studies in an IRI-induced rat model of AKI revealed that BB3 protected the kidney from tubular apoptosis and necrosis (Narayan et al., 2016). These data form the basis of a clinical trial using BB3 in kidney-transplant recipients who present with delayed graft function.

Allograft and isograft renal transplantation can also be used to determine the relative importance of intrinsic renal cells versus bone-marrow-derived cells in the pathogenesis of a wide range of renal diseases. Ex vivo injection of MSCs into the kidney prior to transplantation proved beneficial, whereas systemic injection of MSCs failed to improve recipient survival (Iwai et al., 2014). Recent improvements in the ability to genetically manipulate rats open up an exciting new area of research for renal transplantation studies (Doorschodt et al., 2014).

Conclusions and future perspectives
Disparities between animal models and human disease might have resulted in promising preclinical therapies failing to be effective in clinical trials. Recent developments in genome engineering and transcriptomic profiling now allow the researcher to design and refine models, to more closely interrogate specific aspects of renal disease. The rat has and will continue to play a major role in the identification of key genes that increase disease susceptibility, of early biomarkers that highlight disease progression, and of genes, pathways and cells that are fundamentally involved in kidney regeneration or damage.

As highlighted in this Review, hypoxia, AngII, ACE and P2X7 play key roles in many aspects of kidney damage, placing them at the forefront of therapeutic targets to be explored using rat models. Given the complex nature of, for example, human P2X7 transcripts, humanization of the rat could help to identify which isoforms are disease-promoting, and could aid in the development of novel treatment strategies.
Of particular interest is the application of MSC technology to the treatment of AKI, CKD and renal transplantation. A number of MSC-based clinical trials have been set up, despite safety concerns raised by animal studies (Kunter et al., 2007). In a rat model of glomerulonephritis, MSCs produced a short-term improvement, but ultimately differentiated into intraglomerular adipocytes, resulting in glomerulosclerosis (Kunter et al., 2007). Enhanced recruitment of endogenous MSCs or the use of cell-free cocktails of secreted factors might be preferable approaches (Kunter et al., 2011).

It is important to note that the ‘treatment’ of kidney disease might not lead to repair of all aspects of organ damage. However, the complexity of renal pathologies means that better design and use of rat models as a resource could ultimately result in stratification of diagnosis and tailored therapy.

This article is part of a special subject collection ‘Spotlight on Rat: Translational Impact’, guest edited by Tim Altman and Aron Geurts. See related articles in this collection at http://dmm.biologists.org/collection/rat-disease-model.

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