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### Chronic kidney disease

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(Article begins on next page)

# nature REVIEWS

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1   **Chronic kidney disease**

2   Paola Romagnani<sup>1</sup>, Giuseppe Remuzzi<sup>2</sup>, Richard Glasscock<sup>3</sup>, Adeera Levin<sup>4</sup>, Kitty J. Jager<sup>5</sup>, Marcello

3   Tonelli<sup>6</sup>, Ziad Massy<sup>7</sup>, Christoph Wanner<sup>8</sup> and Hans-Joachim Anders<sup>9</sup>

4   1 Nephrology and Dialysis Unit, Meyer Children's University Hospital, Florence, Italy,  
5   p.romagnani@dfc.unifi.it,

6   2 IRCCS - Istituto di Ricerche Farmacologiche Mario Negri, Bergamo, Italy, Department of Medicine,  
7   Unit of Nephrology and Dialysis, Azienda Socio-Sanitaria Territoriale Papa Giovanni XXIII, Bergamo,  
8   Italy, Department of Biomedical and Clinical Science, L. Sacco, University of Milan, Milan, Italy  
9   gremuzzi@marionegri.it

10   3 Department of Medicine, David Geffen School of Medicine at UCLA, 8 Bethany, Laguna Niguel,  
11   92677 California, USA, rjglasscock@gmail.com

12   4 Division of Nephrology, University of British Columbia, Vancouver, Canada,  
13   alevin@providencehealth.bc.ca

14   5 ERA-EDTA Registry, Department of Medical Informatics, Academic Medical Center, Amsterdam, The  
15   Netherlands, k.j.jager@amc.uva.nl

16   6 Cumming School of Medicine, Division of Nephrology, University of Calgary, Calgary, Alberta,  
17   Canada; Department of Community Health Sciences, University of Calgary, Calgary, Alberta,  
18   Canada, cello@ucalgary.ca

19   7 Division of Nephrology, Ambroise Paré University Hospital, APHP, University of Versailles-Saint-  
20   Quentin-en-Yvelines, Boulogne-Billancourt, and Inserm U1018 Team5, CESP, Villejuif, France,  
21   ziad.massy@aphp.fr

22   8 Department of Medicine, Division of Nephrology, University Hospital of Würzburg, Würzburg,  
23   Germany, Wanner\_C@ukw.de

24   9 Medizinische Klinik und Poliklinik IV, Klinikum der LMU München – Innenstadt, Ziemssenstr. 1,  
25   80336 München, Germany

26   **Correspondence to: H.-J.A.**

27   hjanders@med.uni-muenchen.de

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47 **Abstract**

48 Chronic kidney disease (CKD) is defined by persistent urinary abnormalities or impaired excretory  
49 renal function. While progression to end stage kidney disease (ESKD) is a concern, the majority of  
50 those with CKD are at risk for accelerated cardiovascular disease and death. For those that do reach  
51 ESKD the limited accessibility to kidney replacement therapy is a problem in many locations  
52 worldwide.. Risk factors for CKD include low nephron number at birth and nephron loss due to  
53 increasing age or acute and chronic kidney injuries. For example, the pandemic of obesity and type 2  
54 diabetes largely accounts for the increasing global prevalence of CKD and there is an increasing  
55 awareness of genetic causes for CKD and accelerated CKD progression. The management of CKD is  
56 focused on early detection or prevention, treatment of the root cause if possible, and attention to  
57 secondary processes which contribute to ongoing nephron loss, i.e. remnant nephron hyperfiltration.  
58 Blood pressure control and inhibition of the renin-angiotensin system are the corner stones of  
59 therapy. CKD complications such as CKD complications such as anemia, metabolic acidosis, and  
60 secondary hyperparathyroidism impact cardiovascular health, as well as quality of life, and so require  
61 diagnosis and therapy. Primary prevention of CKD, early diagnosis, and secondary prevention of CKD  
62 progression are needed to reduce cardiovascular disease, CKD-related morbidity, and to prevent  
63 ESKD, whether or not kidney replacement therapies are available.

64

65 **[H1] Introduction**

66 Chronic kidney disease (CKD) is a syndrome defined as persistent alterations in kidney  
67 structure, function or both with implications for health <sup>1</sup>. Examples of structural abnormalities  
68 include cysts, tumors, malformations or atrophy, which become evident by imaging. By contrast,  
69 kidney dysfunction can become evident as hypertension, edema, growth delay in children, and  
70 changes in output or quality of urine; these changes are most often recognized by increased serum  
71 levels of creatinine, cystatin C or blood urea nitrogen. The most common pathological manifestation,

72 regardless of the initiating insult or disease, of CKD is some form of renal fibrosis.

73 The Kidney Disease Improving Global Outcomes (KDIGO) initiative classifies an individual as having

74 CKD if abnormalities of kidney structure or function persist for >3 months. KDIGO describes a

75 classification system based on severity, into numerous stages of CKD using a two dimensional matrix

76 based on estimated or measured glomerular filtration rate (eGFR, mGFR) and on extent of

77 albuminuria (FIG. 1)<sup>1</sup>. Primary care settings often do not assess albuminuria but proteinuria via dip

78 stick analysis, but dip stick +, ++, and +++ usually approximates with the three albuminuria stages.

79 GFR and albuminuria/proteinuria are used to classify CKD because GFR is a well-established marker

80 of renal excretory function and albuminuria is an indicator of renal barrier dysfunction, i.e.

81 glomerular injury. Both have found to be reliable predictors of long term CKD outcomes

82 As the kidney is formed by many independent functional and anatomical 'units', the nephrons GFR,

83 can be expressed by the equation:  $GFR_{(Total)} = GFR_{(single\ nephron)} \times \text{number of nephrons}$ . This implies that

84 when the number of nephrons declines, total GFR will not change as long as single nephrons can

85 increase their individual GFR (known as single-nephron GFR (SNGFR)). Vice versa, a decline in total

86 GFR implies a significant loss of nephrons with remnant nephrons probably operating at their

87 maximum possible SNGFR. That is, CKD can be thought of generally as a loss of functional nephrons

88 but usually represents loss in nephron number. Furthermore, the KDIGO stages are derived from

89 large databases of general, high risk and nephrology populations. The categories define risk of

90 progression to ESKD that is defined as G5 (GFR <15 mL/min/1.73 m<sup>2</sup>) and a number of other

91 outcomes including risk of cardiovascular disease (CVD), death, AKI, infections, and hospitalizations.

92 The KDIGO staging has proven to be very instrumental in decision making on patient

93 management.

94 Whether CKD should be diagnosed and staged using absolute thresholds irrespective

95 of age remains controversial<sup>2,3</sup>. The mGFR in healthy adults aged 20-40 years is about 107

96 ml/min/1.73 m<sup>2</sup> and declines at a rate of about 0.7 ml/min/1.73 m<sup>2</sup> per year<sup>4,5</sup>. By age 75

97 years, many otherwise healthy individuals (without significant co-morbidity) will have lost

98 50% of their nephrons and their GFR that was present at age 25 years<sup>6</sup>. A substantial  
99 number of older healthy individuals have eGFR <60 ml/min/1.73 m<sup>2</sup> and no abnormal  
100 albuminuria (KDIGO CKD G3a A1) meeting the KDIGO criteria for CKD albeit having only a  
101 small increase in relative risk of all-cause mortality<sup>7, 8</sup>. The threshold of GFR that should be  
102 used to detect CKD in younger persons is equally controversial<sup>9</sup>. The upper and lower limits for  
103 mGFR in a 25 year old healthy person being considered as a living kidney donor is about 136 to 78  
104 ml/min/1.73 m<sup>2</sup> respectively<sup>5</sup>; some have suggested that a threshold of <75 ml/min/1.73 m<sup>2</sup> would  
105 be more appropriate for young adults, and values below this threshold are associated with a  
106 significantly increased relative risk of all-cause mortality and ESKD<sup>10</sup>.  
107 The etiology of the impaired kidney function is important, and thus in addition to classifying the  
108 severity of CKD by GFR and albumin levels, understanding the risk factors or causes of CKD is  
109 essential (Box 1), and recommended by the guidelines<sup>1</sup>. In this Primer, we discuss the global  
110 prevalence of CKD, the different diseases underlying poor nephron endowment or nephron loss, the  
111 pathophysiology of CKD progression, the diagnosis, screening, and prevention of CKD, and CKD  
112 management to improve outcomes and quality of life. Finally, we name several research domains  
113 potentially offering improvements for CKD management in the near future.  
114

## 115 [H1] Epidemiology

116 Rates of age-standardized death and disability due to most non-communicable diseases have  
117 decreased over the past 20 years, but such favourable trends are not present for CKD. The Global  
118 Burden of Disease study reports indicate an increase burden of CKD (with substantial worldwide  
119 variation) to which diabetes mellitus seems to be the most important contributor<sup>11-13</sup>. CKD as a cause  
120 of mortality has increased over the last 25 years from 21<sup>st</sup> to 13<sup>th</sup>, and now contributes 1.35% of the  
121 global burden of disability life years lost, growing at a rate of 1% per annum<sup>11, 13, 14</sup>. Note that most  
122 prevalence data are based on levels of GFR only, without consideration of albuminuria, based on the  
123 first CKD classification system reported in 2002.

124

125 **[H2] Prevalence**

126 CKD stage G3–5 prevalence in adults varies worldwide, with values reported as 1.7% in China  
127 <sup>15</sup>, 3.1% in Canada <sup>16</sup>, 5.8% in Australia <sup>17</sup> and 6.7% in the USA <sup>18</sup>. In Europe the range is slightly  
128 narrower: from 2.3% in Germany <sup>19</sup>, 2.4% in Finland <sup>20</sup>, 4.0% in Spain <sup>20</sup> to 5.2% in England <sup>21</sup>. Such  
129 numbers should be viewed with caution because they are often based on a single eGFR assessment  
130 (that is not considering the actual definition, which includes the factor of time (present for >3 mo;  
131 thus it is possible that positive “CKD cases” may overestimate the true prevalence of CKD <sup>22</sup>. The  
132 epidemiology of CKD in low and middle-income countries (LMICs) is poorly characterized due to the  
133 lack of community-based studies, inconsistent assessment of kidney function and non-standardized  
134 or non-calibrated approaches<sup>23</sup>. Nevertheless, in South-East Asia, some Latin American countries  
135 (such as Mexico) and in sub-Saharan Africa, when assessed, the prevalence of CKD appears to be  
136 consistent with the estimates of 10-16% <sup>23-25</sup>.

137

138 **[H2] Risk factors**

139 CKD is more common in people over 65 but the probability of progression to ESKD is higher in  
140 younger people with CKD, albeit sometimes over long period of times <sup>26</sup>. Interestingly, while the  
141 prevalence of CKD is higher in women than in men, men are more likely to progress to ESKD <sup>26</sup>. The  
142 most common underlying diseases are diabetes mellitus and hypertension, particularly in high and  
143 middle income countries. In those with diabetes, CKD prevalence is estimated in 30- 40%. Whether  
144 this is due to diabetes per se or due to microvascular disease is not known. However, in LMICs, CKD  
145 is often due to infectious diseases and glomerulonephritis (a group of diseases that lead to  
146 inflammation of the glomerulus) <sup>27</sup>. Current and future changes in socio-economic circumstances and  
147 population age distributions will increase the absolute number of people with CKD in these countries,  
148 where numbers of elderly persons are rising, and with increasing diabetes and obesity epidemic, may  
149 change the cause of CKD in those populations as well. Furthermore, low birth weight is associated

150 with CKD later in life; the global risks of preterm birth and low birth weight are around 10% and 15%,  
151 respectively. Thus, millions of children are born at risk of CKD later in life and are found at the lower  
152 percentile of age-matched GFR <sup>28, 29</sup>. Specific populations are at higher risk for CKD, in part due to  
153 genetic factors, and others due to interaction of genetic and environmental factors. Those groups at  
154 higher risk include, in alphabetical order: Aboriginal Australians, African Americans, Hispanics,  
155 indigenous populations in Canada, South Asians, Oriental Asians, and Pacific Islanders.

156 Endemic forms of CKD suggest regional triggers, which are often difficult to define among  
157 potential candidates such as specific infections, toxins, behaviours or climate-related factors <sup>30</sup>.  
158 Reports of chronic interstitial nephritis or CKD of undetermined origin (CKDu) in sugar cane and other  
159 agricultural workers in Latin America, Sri Lanka, India, and more recently in Cameroon, Mexico, and  
160 Australia, are examples of this <sup>30-32</sup>.

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## **162 [H2] Children**

163 Little is known about CKD in children because of the absence of registries, and that they are not  
164 included in many clinical studies. In Europe, the 2014 incidence of paediatric ESKD was 5.7 per million  
165 age-related population (pmarp) in children aged 0-14 years and the prevalence 32.2 pmarp <sup>33</sup>. Earlier  
166 estimates suggested the incidence and prevalence were 8.3 pmarp and 58 pmarp, respectively, in  
167 children aged 0-19 years <sup>34</sup>, which is lower than 14.7 pmarp and 103.9 pmarp for the age group 0-21  
168 years in the United States <sup>35</sup>. In high income countries, congenital disorders are responsible for the  
169 majority of cases of paediatric CKD; by contrast, in acquired causes, such as infection and glomerular  
170 diseases, predominate in LMICs <sup>36</sup>.

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## **172 [H2] Kidney replacement**

173 Understanding the information on kidney replacement therapy in the context of CKD is important for  
174 identifying gaps and focusing on solutions to those gaps <sup>37</sup>. Often countries do not know the number  
175 of patients with prevalent CKD but do have information on dialysis numbers. Given that not all

176 people progress to ESKD, estimates of those with CKD can be extrapolated; conversely if CKD rates  
177 are known then numbers on dialysis can reveal inequities in availability of dialysis. Data on the  
178 incidence of kidney replacement therapy for ESKD can only be obtained from countries with dialysis  
179 registries. Data are missing in particular from LMICs, where such registries do not exist. In 2014,  
180 incidence of kidney replacement therapy varied from 49 per million population (pmp) in Bangladesh  
181 to as high as 455 pmp in Taiwan<sup>38</sup>. The majority of patients started kidney replacement therapy on  
182 dialysis, because pre-emptive transplantation as an initial modality is not freely available. Kidney  
183 transplant rates differed substantially by country from 1 pmp in Bangladesh to 60 pmp in Jalisco  
184 (Mexico). There was also huge variation in the prevalence of kidney replacement therapy (FIG. 2):  
185 from 113 pmp in Bangladesh to 3,219 pmp in Taiwan<sup>38</sup>.

186 In many European countries, more than half of all kidney replacement therapy patients are  
187 transplant recipients<sup>38</sup>. This is in contrast to the situation in some Asian countries like Taiwan, Japan  
188 and the Philippines where kidney transplantation is hardly performed<sup>38</sup>. There are multiple reasons  
189 why transplantation is not available despite the availability of expensive dialysis services: cultural,  
190 socioeconomic and health care infrastructure deficiencies (lack of biopsy services, lack of surgeons,  
191 lack of immunology laboratories) account for many of these. Existence of available dialysis and  
192 transplant services has not been systematically documented; however the Global Kidney Health Atlas  
193 [<sup>38</sup>; full report at [www.theisn.org](http://www.theisn.org)] describes availability of kidney replacement therapy worldwide.  
194 Note that the registry data for dialysis and transplantation described above does not reflect the true  
195 need for kidney replacement therapy, which may account for the wide variability in incidence and  
196 prevalence. Estimates of unmet need vary from 2 to 7 million people per year<sup>39</sup>. Note that  
197 availability and accessibility are not the same, and even when services are available in a country or  
198 region, not all individuals may have access to them (depending on cost reimbursement, demand, and  
199 specific policies).

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202

203 **[H1]Mechanisms/pathophysiology**

204 **[H2] Nephron loss and compensation**

205 In humans, nephrons are generated from the 12<sup>th</sup>-36<sup>th</sup> week of gestation with a mean  
206 number of 950,000 per kidney in a range from approximately 200,000 to >2.5 million <sup>40</sup>. No new  
207 nephrons can form upon injury and, during growth from childhood to adulthood, the available  
208 nephrons increase in size to accommodate increased renal demands. However, as people age, GFR  
209 declines (FIG. 3). Although nephrons can deal with transient increases in filtration load (such as upon  
210 food and fluid intake) by transient increases in SNGFR (“renal reserve”) <sup>41, 42</sup>, longer or persistent  
211 increases in body mass (for example, during pregnancy or obesity) promote nephron hypertrophy as  
212 the compensatory mechanism. Any injury- (or kidney donation-)related nephron loss may have the  
213 same effect (FIG. 4). Indeed, either severe kidney injury or combinations of injury with ageing-related  
214 nephron losses — especially in individuals with poor nephron endowment and/or obesity —  
215 accelerates persistent increased SNGFR and loss of remnant nephrons<sup>43</sup>.

216 Remnant nephron hypertrophy is triggered by persistent elevations of SNGFR and filtration  
217 pressure (that is, glomerular hypertension) across the glomerular filtration barrier, which implies  
218 glomerular hyperfiltration. Specifically, glomerular hyperfiltration and hypertension together  
219 promote the release of tumour growth factor-alpha/epithelial growth factor receptor <sup>44, 45</sup>, leading to  
220 nephron hypertrophy that reduces glomerular hypertension by increasing filtration surface <sup>46</sup>.  
221 Indeed, increased SNGFR and remnant nephron hypertrophy allows kidney donors to maintain an  
222 apparently “normal” renal function, despite lacking 50% of nephrons. Obviously, kidney donation  
223 does not necessarily cause CKD progression when donors are carefully selected for good nephron  
224 endowment, the absence of obesity, diabetes, and ongoing nephron injury <sup>47, 48</sup>. However, in other  
225 circumstances, hyperfiltration-driven increases in glomerular dimensions can potentially be harmful  
226 <sup>42, 46, 49-51</sup>. Beyond a certain threshold of hypertrophy, increasing podocyte (which are key octopus-  
227 shaped cells that maintain the glomerular filtration barrier of the nephron shear stress promotes

228 podocyte detachment, focal segmental glomerulosclerosis (FSGS, a pathological entity in which renal  
229 injury results in sclerotic lesions in segments of glomeruli), global glomerulosclerosis and subsequent  
230 nephron atrophy, a vicious cycle further reducing nephron number and the SNGFR of remnant  
231 nephrons (FIG. 5)<sup>44, 46, 52-55</sup>.

232

233 **[H2] Impaired glomerular filtration and fibrosis**

234 Persistent podocyte hypertrophy and glomerular hyperfiltration, maintained by angiotensin II  
235 production, ultimately aggravate podocyte loss and proteinuria, eventually impacting on glomerular  
236 filtration Angiotensin-II, a peptide hormone that is part of the renin-angiotensin system (RAS) and  
237 drives vasoconstriction and aldosterone secretion (and thus sodium retention and an increase of  
238 blood pressure) directly impairs the glomerular barrier sieving function, possibly via inhibiting  
239 expression of the podocyte protein nephrin, a structural component of the slit diaphragm necessary  
240 for maintaining the glomerular filtration barrier independently of its hemodynamic effects<sup>56</sup>.  
241 Angiotensin-II possibly also contributes to the dysregulated response of parietal epithelial cell  
242 precursors along Bowman's capsule, generating FSGS lesions instead of replacing lost podocytes<sup>57</sup>.  
243 This structural remodelling of the glomerular tuft barrier presents clinically as proteinuria.  
244 Proteinuria not only serves as a marker for nephron damage but also predicts CKD progression<sup>44, 58,</sup>  
245<sup>59</sup>. Mechanistically, albuminuria also impairs the capacity of parietal epithelial cells to regenerate  
246 podocytes<sup>44</sup>, instead further promoting the formation of FSGS lesions (FIG. 5)<sup>60, 61</sup>.

247247

248 CKD progression also involves non-specific wound healing responses including interstitial fibrosis.  
249 Albuminuria and complement, and infiltrating immune cells activate proximal tubular epithelial cells  
250 to induce the secretion of and pro-fibrotic mediators followed by interstitial inflammation and  
251 fibrosis<sup>62</sup>. Interstitial fibrosis is frequently considered as an additional factor driving further nephron  
252 injury, e.g. via promoting renal ischemia<sup>62</sup> but, as in other organs, scar formation may also be  
253 essential to mechanically stabilize the remaining nephrons<sup>63</sup>. The increased tubular transport

254 workload of remnant nephrons also involves anaerobic metabolism, intracellular acidosis, and  
255 endoplasmic reticulum stress — all promoting secondary tubular cell injury<sup>44,60</sup>.

256256

**257 [H2]Risk factors**

258 Several factors can contribute to the pathogenesis of CKD, including low birth weight, pregnancy,  
259 obesity, diabetes, and ageing. Each of these scenarios contributes different factors that lead to  
260 and/or exacerbate nephron loss, promoting the cycles of injury and ultimately resulting in kidney  
261 failure.

262262

**263 [H3]Prematurity and low birth weight.**

264 Newborns with low birth weight (owing to preterm birth or intrauterine growth restriction)  
265 frequently display incomplete kidney development<sup>64-66</sup>. Depending on the severity of prematurity,  
266 poor nephron endowment can cause either early childhood CKD or CKD later in life<sup>64-70</sup>. The  
267 associated risk was estimated among US adolescents for every 13 individuals born at low birth  
268 weight, one had reduced GFR and one had raised systolic blood pressure, and this risk increases with  
269 age<sup>29</sup>. The risk of low birth weight infants (<2599 g) to experience CKD up to the age of 17 is fourfold  
270 increased compared to infants with a birth weight of >2500 g (FIG.3B)<sup>69</sup>. CKD onset at puberty is  
271 common in these individuals when rapid body growth exceeds the capacity of nephron number to  
272 accommodate the increasing filtration load<sup>71</sup>. In milder cases, poor nephron endowment at birth  
273 promotes the development of hypertension, CKD later in adults or a faster progression of  
274 glomerulonephritis to ESKD (FIG.3C)<sup>29, 66, 70, 72, 73</sup>. All of these factors increase the risk of  
275 cardiovascular disease.

276

**277 [H3]Genetic factors.**

278 Congenital abnormalities of the kidney and the urinary tract (CAKUT) are the most common  
279 congenital abnormalities<sup>74</sup>. CAKUT present a wide spectrum of causes for kidney hypodysplasia,

280 imparting low nephron number and risk of CKD later in life<sup>75, 76</sup>. Genetic testing has revealed that  
281 ~20% of early-onset CKD (defined as CKD manifesting before 25 years of age) cases can be attributed  
282 to a monogenic cause<sup>77</sup>. Beyond CAKUT, these conditions include ciliopathies, cystic kidney diseases,  
283 tubulopathies, and podocytopathies causing FSGS<sup>75-78</sup>.

284 Until recently, monogenic causes of CKD were mostly reported in children or adolescents, but  
285 genetic variants also contribute as co-factors to CKD progression in adults (FIG. 4). For example, an  
286 *UMOD* gene variant, present on 17% of the alleles in the general population, is associated with CKD  
287<sup>79-81</sup>. Another example is gene variants of apolipoprotein L1 (*APOL1*) in African Americans, which  
288 confer resistance to *Trypanosoma brucei* infections in sub-Saharan Africa<sup>82</sup>. However, these variants  
289 affect endosomal trafficking and autophagic flux, which ultimately leads to podocyte loss,  
290 glomerulosclerosis, nephron loss, and CKD progression<sup>83, 84</sup>. This may explain faster CKD progression  
291 in many patients with sub-Saharan ancestry<sup>82</sup>.

292292

293 **[H3]Obesity.**

294 A larger glomerular size on mildly obese (BMI>30 and <35) but otherwise healthy individuals suggests  
295 an increased SNGFR<sup>85</sup>. In general, the association between obesity and poorer renal outcomes  
296 persists even after adjustments for higher blood pressure and diabetes mellitus, suggesting that  
297 obesity-driven glomerular hyperfiltration directly contributes to nephron loss<sup>86, 87</sup>. Severe obesity  
298 alone or moderate obesity in combination with other factors such as genetic, low nephron number  
299 or aging can lead to development of proteinuria, secondary FSGS, and progressive CKD (FIG. 4)<sup>86, 88-91</sup>.

300300

301 **[H3]Pregnancy.**

302 The latter trimester of pregnancy involves volume expansion (that is, an increase in blood volume)  
303 causing an increase of total GFR by 50%<sup>92</sup>, implying a respective increase of SNGFR. These  
304 physiological adaptations are transient and without consequences in women with normal nephron  
305 number. However, in women with low nephron endowment or previous injury-related CKD (such as

306 in women with lupus nephritis), pregnancy-related glomerular hyperfiltration exacerbates remnant  
307 nephron glomerular hyperfiltration and hypertrophy. In some patients, final trimester pregnancy-  
308 related glomerular hyperfiltration then passes the threshold of compensation and triggers rapid CKD  
309 progression presenting with proteinuria and hypertension — a condition known as eclampsia. Pre-  
310 existing CKD G3A2 or higher, obesity, excessive body weight increase during pregnancy are well-  
311 known risk-factors for eclampsia <sup>93</sup>.

312312

**313 [H3]Diabetes.**

314 Diabetes is a well-known condition associated with massive glomerular hyperfiltration, evident from  
315 increased total GFR and renomegaly <sup>51</sup>. Hyperglycemia promotes the sodium-glucose transporter  
316 (SGLT)-2-driven reabsorption of sodium in the proximal tubule, a process that subsequently  
317 inactivates tubuloglomerular feedback and activates the RAS at the *macula densa* <sup>94, 95</sup>. The result is  
318 induction of a permanent dilation of the afferent arteriole and vasoconstriction of the efferent  
319 arteriole — permanently increasing SNGFR and total GFR <sup>96</sup>.

320 Although diabetes-driven glomerular hyperfiltration can be compensated for many years in  
321 younger patients with normal nephron number, it serves as a drastic accelerator single nephron  
322 hyperfiltration such as patients with low nephron endowment, injury- or ageing-related nephron  
323 loss, obesity or those who are pregnant <sup>97</sup>. Unfortunately, this is a highly prevalent combination of  
324 risk factors in older patients with type 2 diabetes, for which dual SGLT2/RAS inhibition can elicit  
325 potent nephroprotective effects <sup>98</sup>.

326326

**327 [H3]Acute kidney injury.**

328 Acute kidney injury (AKI) is a clinical syndrome defined by an acute deterioration of renal function  
329 resulting in the accumulation of metabolic waste and toxins, subsequent uremic complications, and  
330 potentially failure of other organs <sup>99</sup>. AKI is highly prevalent in hospitalized patients and can imply  
331 irreversible losses in nephron number<sup>100</sup>. In Western countries AKI occurs in both outpatient and

332 inpatient settings, the latter of which is simpler to document, and has been the focus of multiple  
333 papers describing the phenomenon and aiding in the understanding of the strong association  
334 between AKI and CKD. The causes of non hospital/institution-based AKI are diarrhea, infections,  
335 dehydration, medications, while in hospital it can be attributed to these same factors and exposures  
336 to nephrotoxins (dye) and is mostly observed in patients with multiple morbidities<sup>101</sup>. By contrast, in  
337 LMICs and tropical countries, AKI occurs frequently outside the hospital setting following episodes of  
338 diarrhoea, infections and obstetric complications<sup>102</sup>. Nephrotoxins can also cause AKI-related  
339 nephron loss inside and outside hospitals; for example, neonates treated with aminoglycosides,  
340 cancer patients receiving chemotherapy or communities exposed to environmental toxins such as  
341 heavy metals or aristolochic acid can experience AKI episodes<sup>30</sup>.

342342

**343 [H3]Ageing.**

344 The slope of GFR decline varies among individuals depending upon age (FIG. 3), genetic factors, blood  
345 pressure, diseases implying kidney injury and body weight. Histologically, kidney ageing presents as  
346 global glomerulosclerosis, the respective atrophy of entire nephrons, and subsequent interstitial  
347 fibrosis<sup>53, 85</sup>. Whether ageing-related nephron loss is associated with hypertrophy (and glomerular  
348 hyperfiltration) of remnant nephrons is not consistently reported in the literature<sup>53, 85</sup>, but the  
349 analytical difficulties on how to precisely assess nephron number, glomerular volume, and how to  
350 acknowledge the different functions of juxtamedullary versus cortical nephrons can affect the  
351 interpretation of such data<sup>53, 85</sup>. Ageing is associated with decreasing podocyte density and total  
352 numbers<sup>53</sup>. Endomitosis-related mitotic catastrophe and podocyte detachment may contribute to  
353 glomerulosclerosis<sup>53, 103, 104</sup>.

354354

**355 [H2]Systemic effects**

356 The kidney is involved in multiple complex hormonal processes important in anemia, bone  
357 integrity, in regulation of acid base and electrolyte homeostasis, as well as blood pressure control

358 through neuroendocrine and volume sensors. As nephron mass declines, patients will suffer from  
359 complications associated with dysregulation of many of these systems. Anemia, vitamin D deficiency,  
360 hyperparathyroidism, acidosis, hyperkalemia and hyperphosphatemia, hyperuricemia, as well as  
361 hypertension and expansion of effective circulating fluid volume are all clinical manifestations of  
362 these derangements. Interestingly, they do not occur in all individuals at the same point in the  
363 progressive loss of kidney function, and there are some maintain excellent tubular/ excretory  
364 function despite derangements in hormonal function (i.e. severe anemia, and normal electrolytes).  
365 Not all of the derangements are symptomatic, and the severity of the symptoms is variable  
366 between individuals. They include: disorders of fluid and electrolytes, mineral and bone disorder,  
367 anemia, hypertension, dyslipidemia, endocrine abnormalities, in children growth impairment,  
368 decreased clearance of renally excreted substances from the body (eg, hyperuricemia), metabolic  
369 acidosis. Related symptoms may be fatigue, anorexia, weight loss, pruritis, nausea, vomiting,  
370 muscle cramping, edema, shortness of breath, to name a few. None are specific for CKD.

371371

372 **[H3] Fluid and electrolyte abnormalities.**

373 **Sodium and water balance** — Sodium and intravascular volume balance are usually maintained via  
374 homeostatic mechanisms until the GFR falls below 10 to 15 mL/min per 1.73 m<sup>2</sup>. However, the  
375 patient with mild to moderate CKD, despite being in relative volume balance, is less able to respond  
376 to rapid infusions of sodium and is, therefore, prone to fluid overload. In some cases, especially with  
377 an acute water load, hyponatremia and hypertension may occur as a consequence of fluid retention.  
378 Some patients, such as those with nephronophthisis and some with obstructive uropathy, have an  
379 impaired ability to concentrate urine, and have symptoms of polyuria. These children are at risk for  
380 hypovolemia, as they will continue to have large urine losses even when they are volume depleted.  
381 **Hyperkalemia** — In children with CKD, hyperkalemia develops due to reduced GFR causing  
382 inadequate potassium excretion. Also, potassium excretion is dependent upon an exchange with  
383 sodium at the distal tubule. A low GFR decreases delivery of sodium to this site where there is

384 reduction in the exchange rate with potassium into the urinary lumen. Other contributory factors for  
385 hyperkalemia include: high dietary potassium intake, catabolic conditions with increased tissue  
386 breakdown, metabolic acidosis, secondary type IV renal tubular acidosis (RTA) in some patients with  
387 obstructive uropathy, decreased renin production by the juxtaglomerular apparatus, primary or  
388 secondary hypoaldosteronism related to RAS inhibitor-related impaired cellular uptake of potassium

389

390 **[H3]Metabolic acidosis.**

391 Metabolic acidosis is observed in patients with advanced CKD and is related to the fall in total  
392 ammonium excretion that occurs when the GFR decreases to below 40 to 50 mL/min per 1.73  
393 m<sup>2</sup> (GFR category G3). In addition, there is a reduction in both titratable acid excretion (primarily as  
394 phosphate) and bicarbonate reabsorption. As the patient approaches ESKD, the serum bicarbonate  
395 concentration tends to stabilize between 12 and 20 mEq/L. A level <10 mEq/L is unusual, as buffering  
396 of the retained hydrogen ions by various body buffers prevents a progressive fall in the bicarbonate  
397 concentration. In children with CKD, metabolic acidosis has a negative impact on growth.

398398

399 **[H3] Anemia.**

400 The anemia of CKD is due primarily to reduced renal erythropoietin production. The anemia of CKD is  
401 principally normocytic and normochromic. By comparison, the finding of microcytosis may reflect  
402 iron deficiency or aluminum excess, while macrocytosis may be associated with vitamin B12 or folate  
403 deficiency. If left untreated, the anemia of CKD is associated with fatigue, weakness, decreased  
404404 attentiveness, increased somnolence, and poor exercise tolerance.

405405

406 **[H3]Mineral bone disease.**

407 Chronic kidney disease-mineral and bone disorder (CKD-MBD) presents as a broad clinical spectrum  
408 encompassing abnormalities in mineral metabolism, bone structure, and extraskeletal calcifications

409 that are found with progressive CKD. Patients with mild CKD (G2 KDIGO) may have reduced serum

410 calcidiol and/or calcitriol levels, and an elevated serum parathyroid hormone (PTH) and fibroblast  
411 growth factor 23 (FGF-23) level<sup>105</sup>. Patients with more advanced CKD-MBD have bone pain, difficulty  
412 in walking, and/or skeletal deformities and a higher risk of fracture<sup>106</sup>.

413413

**414 [H3]Hypertension.**

415 Hypertension can be present in the earliest stages of CKD, and its prevalence increases with  
416 progressive declines in GFR. Hypertension is high in children with CKD, ranging from 54 to 70 percent  
417 of patients<sup>107</sup>. Hypertension is due to activation of the RAS and volume expansion. In some cases,  
418 hypertension arises from corticosteroids or calcineurin inhibitors such as [cyclosporine](#) or [tacrolimus](#)  
419419 used to treat the underlying kidney disease.

420420

**421 [H3]Dyslipidemia.**

422 Abnormal lipid metabolism is common in patients with CKD and is one of the primary factors that  
423423 increase the risk for CVD.

424424

**425 [H3]Hyperuricemia.**

426 Elevated uric acid levels may develop in patients with CKD due to decreased urinary excretion. Serum  
427 uric acid greater than 7.5 mg/dL is an independent risk factor for accelerated progression of CKD and  
428428 should be treated to have a better outcome.

429429

**430 [H3]Cardiovascular disease.**

431 CVD is the leading cause of death in patients with CKD worldwide<sup>14</sup>. The increased incidence of CVD  
432 is due to the high prevalence of CVD risk factors, such as hypertension, dyslipidemia, hyperuricemia,  
433 abnormal glucose metabolism obesity. Young adults (25 to 34 years) with CKD have at least a 100-  
434 fold higher risk for CVD-related mortality compared with the general population<sup>108</sup>. Patients with a

435 glomerular etiology of CKD and proteinuria were more likely to have CVD risk factors. The CKD-

436 related cardiovascular alterations resemble all aspects of an accelerated ageing process associated  
437 with a shortening of relative telomere length <sup>109</sup>. The vasculature can be affected by both,  
438 atherosclerosis and arteriosclerosis, with lipid-rich plaques but also abundant media calcification. The  
439 burden of atherosclerotic CVD increases in the early stages of CKD, and the burden of non-  
440 atherosclerotic CVD increases in the more advanced stages of CKD. The „two“ diseases involve  
441 different factors that cause distinct changes in the risk factor profile and contribute differently to  
442 outcomes during the course of CKD. Adaptive changes of the heart include left ventricular  
443 hypertrophy (LVH) but also dilatation with subsequent both, systolic and diastolic dysfunction. There  
444 are two different patterns of LVH: concentric LVH, which occurs in the presence of hypertension, and  
445 eccentric LVH, which is associated with volume overload and anemia. Early and sustained induction  
446 of fibroblast growth factor-23 was recently discovered as a driver of LVH in CKD <sup>110</sup>.

447 The absolute risk of cardiovascular events in individuals with pre-dialysis CKD is similar to  
448 that of patients with established coronary artery disease in the general population <sup>111</sup>, and the  
449 increase in risk multifactorial: a higher prevalence of insulin resistance <sup>112</sup>, high blood pressure,  
450 vascular calcification <sup>113, 114</sup>, inflammation and protein-energy wasting <sup>115</sup>. ESKD is associated with a  
451 range of metabolic abnormalities, the so-called milieu of uremic toxicity <sup>116</sup>, activation of the neuro-  
452 hormonal axis <sup>117</sup>, vitamin D receptors <sup>113</sup>, that may all contribute to accelerated ageing of the  
453 vasculature and damage to the heart. Hemodialysis itself may have a direct negative effect on the  
454 heart, so-called myocardial stunning <sup>118</sup>. As a consequence the cardiac and vascular mortality are  
455 several times higher in patients with low GFR or on dialysis than in the general population. Thus, the  
456 risk of CVD in patients who require dialysis depends largely on their cardiovascular health at dialysis  
457 initiation. In patients with healthy arteries, the pre-dialysis management strategy should be  
458 continued to prevent new cardiovascular lesions. Consequently, risk factors for CVD should be  
459 managed intensively in the pre-dialysis period, during transition, and at dialysis initiation.  
460

461 **[H3]Endocrine dysfunction.**

462 In patients with CKD, the following endocrine systems become dysfunctional as kidney function  
463 progressively deteriorates. Each of these is discussed in greater detail separately. There are  
464 abnormalities in gonadal hormones in both male and female patients, which can result in reduced  
465 fertility and sexual problems. In children, these abnormalities result in delayed puberty in two-thirds  
466 of adolescents with ESKD <sup>119</sup>. End-organ resistance to GH due to increased levels of insulin growth  
467 factor binding proteins appears to play a major role in growth impairment in children with CKD <sup>120</sup>.  
468 Abnormalities in thyroid function can also be observed.

**469 [H3]Neurological signs.**

470 Uremia is associated with cognitive alterations in adults and lower performance in all neurocognitive  
471 domains development in children. The neurologic findings can range from seizures and severe  
472 intellectual disability to subtle deficits.

**473 [H3]Sleep and fatigue.**

474 Daytime sleepiness and fatigue are common and increase with decreasing kidney function. Sleep  
475 disorders (restless leg syndrome/paroxysmal leg movements, sleep-disordered breathing, excessive  
476 daytime sleepiness, and insomnia) are also common

**477 [H3]Uremia.**

478 The onset of ESKD (ie, GFR category G5) results in a constellation of signs and symptoms  
479 referred to as uremia. Manifestations of the uremic state include anorexia, nausea, vomiting, growth  
480 retardation, peripheral neuropathy, and central nervous system abnormalities ranging from loss of  
481 concentration and lethargy to seizures, coma, and death. Patients who are uremic also have an  
482 increased tendency to bleed secondary to abnormal platelet adhesion and aggregation properties.  
483 Pericardial disease (pericarditis and pericardial effusion) is an indication to institute dialysis. The  
484 initiation of RRT should be considered  
485

486486

487    **[H1] Diagnosis, screening and prevention**

488    The clinical presentation of CKD depends upon the underlying disorder and the severity of renal  
489    impairment. Patients with early stages of CKD G1-2 are usually asymptomatic. From CKD G3-5  
490    patients may experience weakness related to anemia and polyuria. Only in late stages and in  
491    untreated patients symptoms may include anorexia, vomiting, weakness, and fatigue, which are  
492492    referred to as symptoms of uremia.

493493

494    **[H2]Detection and diagnosis**

495    CKD can be detected during a periodic health assessment in an asymptomatic person or during  
496    evaluation of individuals at risk for CKD (**Box 1**); as a consequence of the incidental finding of  
497    abnormal laboratory values in connection with an acute or chronic illness; during an investigation of  
498    symptoms and/or signs relating to the kidneys or urinary tract (such as haematuria); or during  
499    discovery of abnormal laboratory values in a population-based screening program. Importantly, the  
500    two biochemical parameters (GFR and proteinuria) used in the aforementioned KDIGO matrix<sup>1</sup> define  
501    and classify a “generic” form of CKD, and adding an etiological diagnosis is both highly desirable and  
502    recommended by KDIGO (The Cause/GFR/Albuminuria [CGA] classifications system), whenever  
503    possible, such that the underlying conditions can be treated first to halt progression of CKD.  
504    Progression is defined according to changes in eGFR by KDIGO<sup>1</sup>. Several tests can be performed to  
505    confirm a CKD diagnosis and identify its cause. It must be stressed that a diagnosis of CKD, according  
506    to the KDIGO construct, requires persistence or progression of the defining abnormality for at least 3  
507507    months. A single value of GFR or albuminuria is insufficient and if used for diagnosis of CKD will lead  
508508

509    **[H3] Measuring and estimating GFR.**

510    First, the assessment begins with measurement of serum creatinine concentration (under steady-  
511    state conditions) and applying formulas for estimated GFR (eGFR – creatinine, like CKD-EPI eGFR-

512 creatinine). It must be recognized that the results of these creatinine based tests can be influenced  
513 by changes in muscle bulk (atrophy or hypertrophy), dietary intake of cooked red meat (strict vegan  
514 diet) and alterations in tubular secretion of creatinine from exposure to drugs (e.g. trimethoprim-  
515 sulfamethoxazole)<sup>121, 122</sup>. Alternative approaches using serum cystatin\_C concentrations have also  
516 been proposed. While not influenced by muscled bulk and diet, the cystatin C -based formulas for  
517 eGFR can be affected by inflammation, obesity, thyroid disease, diabetes, and steroid administration  
518<sup>123</sup>. Second, some eGFR formulas have not been extensively validated in older subjects and may not  
519 apply to Asians or Africans<sup>124, 125</sup>. Third, the requirements for inclusion of demographic variables of  
520 age and gender, to correct for differences in creatinine generation, may also create unwanted  
521 complications in determining prognostic implications of a calculated GFR. Newer eGFR formulas such  
522 as FAS (full age spectrum) or CKD-EPI using serum creatinine, cystatin C or a combination of Cystatin  
523 C or a combination of both have improved accuracy to predict mGFR<sup>126, 127</sup>. Although cumbersome  
524 and expensive, mGFR assessments using urinary clearance methodology can sometimes be needed,  
525 but applying methods of plasma clearance of Iohexol or of radiolabelled lothalamate could avoid  
526 some of these issues. In well-defined circumstances, such as stratifying long term risks of uni-  
527 nephrectomy for potential living kidney donors, such studies can be useful<sup>128, 129</sup>. As mentioned in  
528 the introduction, caution should be exercised in using a fixed and arbitrary threshold of  
529 <60ml/min/1.73m<sup>2</sup> of GFR alone (in the absence of abnormal proteinuria or imaging) for the  
530 diagnosis of CKD in older or elderly adults. A GFR of 45-59ml/min/1.73m<sup>2</sup> is fairly common in  
531 otherwise healthy seniors, depending on their age, due to the normal physiologic loss of nephrons  
532 and GFR with organ senescence<sup>130</sup>.

533533

534 **[H3]Measuring proteinuria.**

535 Abnormal rates of urinary excretion of albumin or total protein are essential for detection of  
536 CKD when GFR is normal and contribute to the assessment of prognosis<sup>131</sup>. Proteinuria (or  
537 albuminuria) can be determined in multiple ways, including simple “dip stick” qualitative methods,

538 point-of-care urinary albumin concentration tests, random un-timed urine samples for calculation of  
539 urine protein (or albumin) to creatinine ratios (UPCR or UACR in mg/mg or mg/mmol), or timed 24  
540 hour urine collections and measuring absolute protein or albumin excretion<sup>132, 133</sup>. Each of these has  
541 advantages and pitfalls. But it is important to recognise that not all patients with CKD have abnormal  
542 urinary protein excretion. For example, early in the course of Autosomal Dominant Polycystic Kidney  
543 Disease the urinary protein exertion is normal only slightly increased<sup>134</sup>.

544 Urinary protein or albumin excretion is more variable than serum creatinine levels, and can  
545 be influenced by posture, activity, fever or drugs so multiple specimens must be collected to enhance  
546 reliability. UPCR and UACR methods can be influenced by the prevailing urinary creatinine excretion  
547 rate; i.e. low creatinine excretion (from sarcopenia) can increase UPCR or UACR values even at  
548 normal absolute protein or albumin excretion rates. Hence, adjusting for the effect of urinary  
549 creatinine excretion can enhance the accuracy of UPCR and UACR measurements<sup>132, 133</sup>.

550 In the KDIGO schema, UACR values are divided into three categories<sup>1</sup>, namely, normal or  
551 low, which is <30 mg/g creatinine (<3.0 mg/mmol, formerly “normo-albuminuria”); moderately  
552 increased, which is ≥30-299 mg/g creatinine (>3.0-29 mg/mmol, formerly “micro-albuminuria”); and  
553 severely increased, which is ≥300 mg/g creatinine (30 mg/mmol, formerly “macro-albuminuria”).  
554 Even with a normal eGFR, CKD can be diagnosed with persistent UACR of >30 mg/g creatinine. Each  
555 incremental increase in UACR is associated with an increased risk of mortality and ESKD, so sustained  
556 albuminuria (or proteinuria) is a powerful prognostic marker.

557 The corresponding “dipstick” (urinalysis test strip) values (and protein concentration in  
558 mg/dL) are negative (<10 mg/dL) to trace (10-15 mg/dL) for normal, 1+ (30 mg/dL) for moderate and  
559 2+ (>100 mg/dL) or greater for severe proteinuria. Persistent proteinuria of >1+ is a good predictor of  
560 a tendency for CKD progression, i.e. GFR decline of > 5 ml/min/1.73 m<sup>2</sup>/year or 7 times the normal  
561 rate of loss with ageing<sup>135</sup>. Thus, albuminuria or proteinuria allow early detection of CKD (see  
562 Screening below), but several forms of progressive CKD can present with normal or only slightly  
563 increased albumin or protein excretion, especially tubulo-interstitial diseases such as autosomal

564 dominant polycystic kidney disease <sup>134</sup>. Marked proteinuria (in excess of 3.5 g/d in and adult),  
565 especially when accompanied by a reduction in serum albumin concentration (referred to as  
566 “nephrotic syndrome”) nearly always implies a diagnosis of a primary or secondary glomerulopathy  
567 underlying CKD <sup>136</sup>.

568568

569 **[H3]Biopsy and pathology.**

570 Percutaneous kidney biopsy is a very valuable tool in assessment of the underlying cause for CKD.  
571 The indications for performance of a renal biopsy in a patient with CKD depends upon the benefits to  
572 be obtained (precise diagnosis, better prognosis, appropriate therapy) and the risks of a biopsy-  
573 related complications. Kidney biopsies are commonly recommended for adult patients with  
574 nephrotic syndrome (urine protein excretion of >3.5 g/d and serum albumin levels <3.5 g/dL) but  
575 may also be indicated for evaluation of unexplained rapidly progressive loss of kidney function,  
576 persistent hematuria and low-grade- proteinuria (0.5-3 g/d), of even isolated proteinuria (1-3 g/d) <sup>137</sup>.  
577 Depending on the circumstances leading to the procedure, the pathologic findings can vary widely,  
578 but in states of marked proteinuria glomerular diseases are most likely to be seen. The degree of  
579 tubule-interstitial scarring can provide useful prognostic information. The risks of renal biopsy are  
580 minimal in experienced hands, and complications are mostly related to post-biopsy bleeding. Fatal  
581 complications are rare (about 1:20,000). Major complications, such as nephrectomy or transfusion  
582 requiring bleeding are more common (about 1:250-500) <sup>138, 139</sup>.

583583

584 **[H3]Other tests.**

585 Continuing advances in the field of serum and urine proteomics, microRNA biology and in serology  
586 are providing many new powerful and non-invasive tools to identify specific diseases or groups of  
587 diseases that may revolutionize the approach to detecting and diagnosing CKD in the future <sup>140</sup>.  
588 These new tools may also expand the horizon of prognosis into new areas beyond GFR and  
589 proteinuria estimation — giving rise to exciting new possibilities for “precision” medicine whereby

590 care of CKD is personalized based diagnostic and prognostic characteristics. Unfortunately, many  
591 patients with CKD are only recognized in the later stage of the disease (Categories G3B-G5) where  
592 CKD complications such anemia, metabolic acidosis, mineral-bone disease provide additional  
593 593 diagnostic clues.

594 594

595 In addition, both detection and diagnosis of CKD, also rely on renal imaging (ultrasonography, CT and  
596 MRI), careful examination of the urinary sediment, and specialized biochemical and serologic tests  
597 suitable to detect specific disorders causing CKD (**Box 2**). Imaging tests are particularly valuable as  
598 they provide information on kidney size, contours, location, and density as well as anatomy of the  
599 urinary drainage system (pelvis, ureters and bladder). Specific lesions, such as cysts, dilation of  
600 ureters or pelvis, calcification, masses, scars can provide valuable clues to the cause of CKD or even  
601 generate a specific diagnosis (such as autosomal dominant polycystic kidney disease or obstructive  
602 uropathy)<sup>141</sup>. Then urine sediment examination is important for the detection and quantification of  
603 haematuria, leukocyturia and casts.

604 Genetic testing is also emerging as an important tool for diagnosing CKD, particularly in children or  
605 young adults. Autosomal dominant polycystic kidney disease, podocytopathies causing steroid-  
606 resistant nephrotic syndrome, Fabry's disease, Alport syndrome, are other well-known entities  
607 requiring a genetic diagnosis. Using next-generation sequencing displays an unexpected genetic  
608 heterogeneity and alterations in numerous different genes in a significant proportion of not only  
609 familial or syndromic patients but also in sporadic cases of CKD. These observations imply the need  
610 for updating the current management in terms of diagnostic algorithms and therapeutic choices<sup>77,</sup>  
611 <sup>142</sup>.

612

## 613 **[H2]Screening**

614 In the context of CKD, screening can take two forms: population screening, for example, using  
615 "dipstick" urinary testing of school children or soldiers; or "opportunistic screening", whereby

616 physician encounters for other medical reasons can be used to screen for CKD. Population-based  
617 screening can be further divided into general population screening or “targeted” screening of high-  
618 risk population groups (such as diabetic or family members related to subjects with diagnosed CKD).  
619 Unfortunately, the benefits and harms of both forms of screening for CKD have not been rigorously  
620 tested in long-term prospective studies, so the overall benefits and harms of population-based  
621 screening for CKD are poorly understood and further trials are needed <sup>143, 144</sup>. Population-based  
622 screening for CKD is not recommended by the United States Preventive Task Force largely due to  
623 insufficient evidence of benefit (or harm) <sup>145</sup>. Evidence in favor of case-finding (i.e., testing for CKD in  
624 people with recognized risk factors, such as hypertension or diabetes) is slightly better, but still  
625 incomplete. Accordingly, the American College of Physicians determined that current evidence was  
626 insufficient to evaluate the benefits (or harms) of screening and case-finding for CKD <sup>146</sup>. The position  
627 on screening for CKD varies widely around the world, with several countries having long-established  
628 programs (Japan and Singapore for example) and others that have introduced them as part of  
629 universal health care systems systems (The United Kingdom for example) <sup>147-151</sup>.

630 Both screening and case-finding for CKD are logically hampered by the need for re-  
631 evaluation at a defined interval to fulfil the duration requirement for diagnosis. Therefore, one-off  
632 testing using eGFR or proteinuria has a high “false positive” detection/diagnosis rate, and possible  
633 misclassification of subjects by use of a fixed (non-age-sensitive) eGFR thresholds, as discussed. The  
634 potential harms of general population screening involve excessive follow-up diagnostic procedures,  
635 unnecessary referral of subjects erroneously diagnosed as having CKD, the anxiety induced by being  
636 labelled as having CKD, and potential impact on insurability. Nevertheless, several national kidney  
637 organizations advocate screening for CKD. Monte Carlo simulations support case-finding strategies in  
638 diabetic subjects for albuminuria or hypertension <sup>152</sup>, because early treatment may offer significant  
639 effects on delaying CKD progression and ESKD <sup>153</sup>. Some studies have suggested that testing for  
640 abnormal albuminuria may be an efficient way of stratifying populations for more intensive search  
641 for modifiable risk factors for CKD and cardio-vascular events, such as hypertension and diabetes <sup>154</sup>.

642 Indeed, abnormal proteinuria (even only slightly above the upper limit of normal) identifies people at  
643 greater risk for ESKD and/or cardiovascular morbidity and mortality <sup>155</sup>. As mentioned before,  
644 population screening for CKD using eGFR tends to substantially over-diagnose CKD in older subjects  
645 with no or minimal proteinuria. Opportunistic testing for CKD has much merit, especially if the  
646 subjects have other risk factors such as diabetes, hypertension, or a family history of CKD. In such  
647 patients an eGFR should be assessed along with an estimate of albuminuria or total protein excretion  
648 ("dipstick"), UACR or UPCR- adjusted for creatinine excretion rate). It also must be appreciated that  
649 older subjects with CKD G3 (as defined by KDIGO, see above) detected in screening programs or  
650 otherwise in primary care practices tend to have a rather benign prognosis, at least over the short  
651 term of 5 years or less. Shardlow et al found a very low rate of ESKD (0.2%) and stable or remission  
652 of CKD was found in 53% of such subjects (average age 73 years at entry) after 5 years of follow-up

653 653 <sup>156</sup>.

654 Finally, there are a few special circumstances where testing of apparently healthy individuals  
655 for CKD may be indicated. For example, first degree relatives of a patient with autosomal-dominant  
656 polycystic kidney disease (ADPKD) are eligible for screening with renal ultrasound or MRI regardless  
657 of results of eGFR or proteinuria. Siblings of patients with Fabry's disease, Alport syndrome, or thin  
658 basement membrane nephropathy might also benefit from genetic analysis as well. African-  
659 Americans with hypertension or HIV infection may receive more informed prognosis by assessment  
660 of *APOL1* risk alleles, but population-based screening for *APOL1* risk alleles is not yet justifiable <sup>157</sup>

661 661

## 662 [H2]Prevention

663 From a societal perspective, prevention of CKD is preferable to after-the-fact treatment of kidney  
664 disease at its end-stage by dialysis or transplantation. Both primary prevention (occurring before CKD  
665 is established) and secondary prevention (initiated to slow the rate of CKD progression or to affect  
666 the associated co-morbidities or complications; see below, Management) should be considered.

667 Primary prevention attacks the root causes of CKD and includes mitigating exposures to

668 nephrotoxic agents and events (Box 1). Reduction of the burden of infectious diseases (such as HIV,  
669 Malaria, *Streptococcus* infection) have already yielded some protection from CKD, but many  
670 challenges remain. Preventing obesity and the associated type 2 diabetes mellitus is a global  
671 challenge<sup>158</sup>. The discovery of a central role for sugar and fructose intake and metabolism in obesity  
672 can be cited as an example of progress with implications for primary prevention. Indeed, better  
673 glycemic control may also eventually prevent CKD and its progression<sup>153, 159-161</sup>. Improved recognition  
674 and reduction of the prevalence of AKI may also have dividends on prevention of CKD, especially in  
675 counties where AKI is common, under-recognized and under-treated such as equatorial Africa. Given  
676 the importance of low nephron endowment, fetal malnutrition and/or dysmaturity and manifested  
677 by low birth weight, global efforts to reduce fetal malnutrition and dysmaturity should have  
678 enormous “pay-back” in later years and focussed effects are beginning to address this important  
679 topic<sup>66</sup>.

680680

## 681 [H1] Management

682 Several aspects need to be considered when managing patients with CKD: controlling nephron injury,  
683 normalizing single nephron hyperfiltration, controlling CKD-related complications, and preparing the  
684 patient for kidney replacement therapy. At the core of these is the principle of ‘the earlier-the  
685 better’, which is the effort to reduce the progression to ESKD and optimize renal outcomes.

686 The impact of early therapy is well documented for Alport syndrome<sup>162</sup>. Initiating RAS  
687 blockade based on the genetic diagnosis before any signs of kidney disease can have dramatic effects  
688 on renal outcomes, whereas initiating RAS blockade as late as CKD G3 only somewhat delayed ESKD  
689 (FIG. 6)<sup>162</sup>. Further support comes from a posthoc analysis of clinical trials testing RAS blockade in  
690 diabetic kidney disease. The effect on gaining ESKD-free years was highest when RAS blockade was  
691 initiated at the time of microalbuminuria and lowest when initiated once a diagnosis of CKD G3 or G4  
692 was made<sup>163</sup>. Therefore, early diagnosis and treatment are essential to prevent nephron loss from as  
693 early as possible.

694694

695 [H2]Controlling ongoing nephron injury

696 Nephron injury can be driven numerous triggers (Table 1), and abrogating these triggers will slow  
697 progression to CKD and ESKD. For example, genetic abnormalities can cause CKD either by fostering  
698 nephrocalcinosis <sup>164</sup>, cystic degeneration or by weakening epithelial integrity such as in genetic  
699 podocytopathies or in abnormal processing or storage of metabolites or glycoproteins <sup>78, 165</sup>. Specific  
700 cures for genetic kidney diseases exist in some forms and are mostly limited to enzyme replacement  
701 therapy or substrate supplementation (Table 1). The genetic basis of immune-mediated nephron  
702 injury is not yet fully explored but C3 glomerulonephritis or atypical hemolytic uremic syndrome  
703 (aHUS) can be controlled with complement inhibitors, an area of intense and promising research <sup>166</sup>.  
704 Most acute forms of immune-mediated nephron injury present either as vasculitis, immune complex  
705 glomerulonephritis or interstitial nephritis (including allograft rejection). These disorders can often  
706 be targeted with immunomodulatory drugs (and sometimes with plasma exchange) to limit nephron  
707 loss from attack by the humoral and/or cellular elements of the immune system <sup>167</sup>.

708 In contrast, in smoldering immune injury, such as in chronic IgA nephropathy, it is difficult to  
709 dissect CKD progression driven by immune versus non-immune mechanisms and the efficacy of  
710 immunosuppression versus RAS blockade and blood pressure control is less evident <sup>168</sup>. Kidney biopsy  
711 may establish the diagnosis and can also guide management by assessing the ongoing activity of  
712 immune injury versus irreversible damage, e.g. in lupus nephritis, IgA nephropathy or allograft  
713 dysfunction. Specific treatments are also available for CKD related to urinary tract obstruction,  
714 infections, and some forms of toxic injury (Table 1). However, even upon complete abrogation of the  
715 injurious trigger, recovery of lost nephrons is impossible.

716716

717 [H3]Preventing any avoidable injury of remnant nephrons.

718 Avoiding further episodes of AKI is crucial to minimize stress on the remnant nephrons in CKD  
719 kidneys. This implies patient education on avoidable nephrotoxins such as radio contrast media,

720 NSAIDs, certain antibiotics or other endemic or occupational toxins. Hypovolemic states as well as  
721 urinary outflow obstruction should be avoided. Additionally, not every asymptomatic leukocyturia  
722 implies bacterial infection and antibiotic treatment should be limited to the presence of dysuria,  
723 bacteruria, and leukocyturia. Smoking cessation is essential minimize CVD<sup>169</sup>.

724

725 **[H2] Normalizing single nephron hyperfiltration**

726 Rigorous RAS inhibition with ACE inhibitors (ACEi) or angiotensin receptor blockers (ARBs) has the  
727 capacity to substantially reduce SNGFR and glomerular filtration pressure, which leads to a decline in  
728 not only proteinuria but also total GFR — and, hence, moderately increases serum creatinine levels  
729<sup>170</sup>. At first, this serum creatinine increase is worrisome to patients (and physicians) and requires  
730 clarification that reducing hyperfiltration in remnant nephrons is the central strategy to retard CKD  
731 progression in patients with proteinuria. In contrast, ACEi or ARBs do not retard the progression of  
732 non-proteinuric forms of CKD such as ADPKD but still may have benefits on the associated  
733 cardiovascular complications<sup>171</sup>. ACEi or ARBs should be titrated to the maximal possible dose, while  
734 hyperkalemia can be corrected using loop diuretics or potassium-binding resins<sup>172</sup>. A moderate  
735 increase in serum creatinine levels indicates a decline in SNGFR, which is a powerful predictor of the  
736 intended nephroprotective effect<sup>173</sup>. Numerous RCTs have documented the class effect of RAS  
737 inhibitors to retard or even halt CKD progression<sup>44</sup>. Reducing dietary salt and drugs that support  
738 control of blood pressure and hyperlipidemia, often referred to as “remission clinic protocol”, may  
739 further reduce proteinuria and retard CKD progression<sup>174, 175</sup>. Such interventions are affordable and  
740 are of importance where kidney replacement therapy is not available or affordable.

741 Avoiding or correcting obesity can also reduce filtration load and glomerular hypertension;  
742 hence, a normal BMI is a treatment target to retard CKD progression<sup>176</sup>. Any immunosuppression-  
743 related benefit of using steroids in CKD may be counterbalanced by steroid-related obesity that  
744 drives glomerular hyperfiltration and secondary FSGS, which could explain why steroid treatment  
745 falls short in retarding progression of IgA nephropathy-related CKD<sup>168</sup>. Finally, concomitant diabetes

746 has important implications for CKD management <sup>177</sup>. Hyperglycemia maximizes glomerular  
747 hyperfiltration via SGLT2-driven vasodilation of the afferent arteriole of the remnant nephrons,  
748 which cannot be controlled by RAS inhibitors <sup>94</sup>. Recently, SGLT2 inhibitors have been shown to  
749 reverse this process and elicit profound additive nephroprotective effects on CKD progression <sup>98, 178</sup>.  
750 Their capacity to also reduce CVD (in patients with type 2 diabetes) <sup>178, 179</sup> provides a strong rationale  
751 751 for dual RAS/SGLT2 blockade in patients with diabetes and CKD.

752 752

### 753 [H2]Controlling CKD complications

754 CKD is associated with a number of secondary complications that require management (Box 3), the  
755 most relevant of which in terms of overall mortality is CVD <sup>14</sup>. Cardiac and vascular alterations also  
756 arise from endocrine failure (e.g. lack of erythropoietin, vitamin D, parathyroid hormone), which  
757 causes anemia and secondary hyperparathyroidism <sup>180</sup>. Myocardial fibrosis is the final consequence  
758 of the multiple underlying causes.

759 Large randomized controlled trials in patients on hemodialysis have tested a number of  
760 different interventions intended to reduce cardiovascular events such as dialysis dose and flux,  
761 erythropoietin-stimulating agents, statins, RAS blockade, folic acid, cinacalcet or vitamin D  
762 derivatives but have largely been unsuccessful <sup>181-183</sup>. For example, statins may prevent  
763 cardiovascular events in patients on dialysis, but the magnitude of any relative reduction in risk is  
764 substantially smaller as compared to what can be achieved in CKD 2-4 <sup>183-186</sup>. For example, reduction  
765 of LDL cholesterol with simvastatin plus ezetimibe reduced the incidence of major atherosclerotic  
766 events more efficiently in patients with CKD G2-4 than with CKD G5 or 5D <sup>183</sup>. Hence, early  
767 intervention with standard-of-care is essential in patients with CKD 2-4. In parallel, similar concepts  
768 for cardiovascular protection are administered for progression of diabetic and non-diabetic kidney  
769 disease. For these patients, guideline-directed approaches to achieve target blood pressure through  
770 administration of RAS blockers, salt restriction and anemia prevention is the mainstay of therapy <sup>187</sup>.

771     <sup>188</sup>. Guidance is also available for the correction of acidosis and mineral and bone metabolism  
772     disorders (**Box 3**)<sup>189</sup>.

773773

**774     [H2]Preparing for kidney replacement therapy**

775     ESKD typically requires renal replacement therapy, although conservative treatment is a potential  
776     alternative option, especially in older adults with limited life span. Counseling on the options (kidney  
777     transplant, hemodialysis, peritoneal dialysis or no dialysis) should be coordinated by the nephrologist  
778     and involve a multidisciplinary team including the general practitioner. Early counseling is essential  
779     because informed patients are better prepared to face kidney failure. Indeed, late referral, i.e. at the  
780     time of ESKD, is associated with worse health status at the time of kidney replacement therapy  
781     initiation, higher mortality after starting dialysis, and decreased access to transplant<sup>190</sup>. However,  
782     one of the biggest challenges nephrologists face is to predict kidney disease progression, which does  
783     not follow a steady linear decline. This unpredictability often becomes a barrier to timely shared  
784     decision making between patients and physicians and could lead to adverse patient outcomes<sup>190</sup>,  
785     and may offset the relationship between the early pre-dialysis nephrology care for adults with late  
786     stage of CKD and improved outcomes<sup>191</sup>. KDIGO suggested that dialysis be initiated when one or  
787     more of the following are present: symptoms or signs attributable to kidney failure (serositis, acid-  
788     base or electrolyte abnormalities, pruritus); inability to control volume status or blood pressure; a  
789     progressive deterioration in nutritional status refractory to dietary intervention; or cognitive-  
790     impairment<sup>1</sup>. This often but not invariably occurs in the GFR range between 5 and 10  
791     ml/min/1.73m<sup>2</sup>. Moreover, living donor preemptive renal transplantation in adults should be  
792     considered when the GFR is <20 ml/min/1.73m<sup>2</sup>, and there is evidence of progressive and irreversible  
793     CKD over the preceding 6-12 months<sup>1</sup>.

794794

**795     [H3]Hemodialysis.**

796     In 1945 Willem Kolff was the first to successfully treat kidney failure of a patient by performing

797 hemodialysis using an artificial kidney able to clear blood from uremic toxins<sup>192</sup>. Since then numerous  
798 technical innovations have optimized the procedure that meanwhile has become available (but not  
799 everywhere affordable) all over the world<sup>38</sup>. Preparing patients for hemodialysis involves referral for  
800 vascular access placement. The types of access include arteriovenous fistulae, arteriovenous grafts  
801 and central venous catheters (which are for short-term use) (FIG. 7A-C); arteriovenous access is the  
802 preferred option for hemodialysis, although there is no consensus about the optimal timing for  
803 creation, especially for arteriovenous fistulae<sup>193</sup>. To protect the blood vessels for permanent vascular  
804 access, attention should be taken to avoid venous puncture or intravenous catheter placement  
805 proximal to the wrist, which implies that venous puncture at the back of the hand still being possible.  
806 Arteriovenous access (either fistulae or grafts) is associated with better outcomes than central  
807 venous catheters<sup>194 195</sup>. Patients with a central venous catheter have poorer survival than those who  
808 subsequently convert to functional arteriovenous access<sup>196</sup>. Thus, a functional arteriovenous access  
809 is preferable for all patients in which the vascular status allows to install a fistula.  
810

### 811 [H3]Peritoneal dialysis.

812 Peritoneal dialysis is another way to eliminate uremic toxins from the blood using the  
813 peritoneal membrane as an exchange interface. For this a transcutaneous catheter is implanted into  
814 the peritoneal cavity that allows repetitive daily drainage and refills of dialysate fluid. After some  
815 hours of reaching equilibrium between uremic blood and fresh dialysate each dwell is expected to  
816 drain excess fluid, metabolic waste products including uremic toxins (FIG. 7D). There are published  
817 guidelines regarding insertion and perioperative management of peritoneal dialysis catheters. A  
818 peritoneal dialysis catheter may be ready for use after 2 to 3 weeks. However, there is marked  
819 variability in peritoneal dialysis catheter insertion techniques (open surgery, blind via trocar or blind  
820 via Seldinger technique) and perioperative management<sup>197</sup>. Interestingly, patients starting on  
821 peritoneal dialysis show better initial outcome and preservation of residual renal function, especially  
822 in the first 2 years as compared to patients on hemodialysis<sup>198</sup>.

823823

824     **[H3]Kidney transplantation.**

825     When available, suitability for kidney transplantation should be evaluated according to age and co-  
826     morbidity, but it may take months to complete <sup>199</sup>. Co-morbidities such as cancer, chronic  
827     infections, cardiac or peripheral vascular disease, and the risk for medical noncompliance are  
828     carefully evaluated in this process. Depending on the regional ratio of donors to recipients and on  
829     allocation rules, waiting time for a deceased donor kidney can vary from a few months (e.g. Belgium,  
830     Austria) to many years (e.g. Germany). Thus, the option of living kidney donation should be explored.

831                 To test for eligibility, potential donors must undergo a comprehensive health assessment  
832     including tests for blood group and human leukocyte antigen compatibility with the potential  
833     recipient, GFR measures, imaging of the kidneys and the urinary tract, cardiac testing, and other tests  
834     depending on the medical history. This is because, the donor's short and long-term well-being after  
835     donation remains a first priorityPre-emptive transplantation (kidney transplantation before even  
836     initiating dialysis) may offer several benefits to ESKD patients but its impacts remain under  
837     evaluation <sup>200</sup>. The half-life of a transplanted kidney is <20 years, making these patients also potential  
838     candidates for CKD treatments during their life span <sup>201</sup>. For example, recurrent glomerulonephritis is  
839     an unpredictable complication that can have a negative impact on graft outcome <sup>202</sup>.

840

841     **[H2]Conservative treatment/palliative care**

842     Kidney replacement therapy may not be available or affordable but it may also not be advisable for  
843     medical reasons. Especially in very old ESKD patients, dialysis may neither increase life span nor  
844     improve quality of life (QOL) <sup>203-205</sup>: in such cases palliative (trying to control the symptoms of uremia  
845     affecting QOL <sup>206</sup>) and education starting at CKD G4 (aimed at explaining comorbidity management)  
846     may be appropriate. Withdrawal from dialysis is a related issue and is common in very old  
847     hemodialysis patients <sup>207</sup>.

848848

849 [H1] Quality of life

850 CKD-related symptoms increase along CKD progresses and are key drivers of poor QOL in patients  
851 with CKD and ESRKD <sup>208-210</sup>. In contrast, symptoms rapidly improve upon kidney transplantation.  
852 Symptoms are most severe in dialysis patients, who frequently report fatigue, nausea, dyspnea,  
853 anorexia, pruritus, restless legs, and cramps <sup>211</sup>. Pain is especially common: in a survey of 205  
854 prevalent patients on hemodialysis, approximately 25% had “severe” pain during the 24h preceding  
855 the interview, and an additional 12% had “moderate pain” <sup>212</sup>. Mental illness including depression  
856 and anxiety are also common <sup>213</sup>, but are understudied among people with CKD. Unfortunately,  
857 clinical and epidemiological characteristics associated with the presence, severity, onset and  
858 remission of uremic symptoms are incompletely described; their pathophysiology is poorly  
859 understood; and few drugs have been approved by regulatory authorities for their treatment <sup>214</sup>.

860 Comorbidity and complications of CKD also substantially contribute to the reduced QOL in  
861 CKD patients. In some cases (e.g. anemia), effective treatments are available. In others, treatment is  
862 technically possible but has significant limitations, and treatment itself frequently causes additional  
863 symptoms and morbidity (e.g. dialytic management of hypervolemia). Despite the best efforts of  
864 clinicians, interactions between complications and their treatments can further compromise QOL for  
865 patients (e.g. volume overload resulting from sodium bicarbonate treatment of acidosis).  
866 Management of multiple comorbid conditions is already complex in patients with normal kidney  
867 function <sup>215</sup>; the situation is even more challenging in people with CKD, where the pathophysiology  
868 and optimal treatment of common coexisting conditions may differ from the general population (e.g.  
869 statins for coronary disease in dialysis patients). Lack of knowledge about how to prioritize and  
870 manage comorbid conditions undoubtedly contributes to the lower QOL in CKD patients through  
871 multiple mechanisms – including drug-drug and drug-condition interactions; pill burden; and  
872 decisional conflict for patients.

873 Dialysis is an effective life-support treatment but has many limitations in addition to those  
874 mentioned above. Key challenges for hemodialysis that specifically compromise QOL include poor

875 functional status (driven in part by procedure-related immobilisation, uremia-related malnutrition,  
876 and muscle wasting), the intrusive and time-consuming nature of the treatment, and vascular access  
877 infection and dysfunction<sup>216</sup>. Instruction for some home-based, low intensity physical exercise can  
878 improve physical performance and QOL in patients on hemodialysis<sup>217</sup>. Peritoneal dialysis also poses  
879 significant challenges for QOL including gastrointestinal distension, hernias, and chronic volume  
880 overload. Both forms of dialysis make employment difficult and both are associated with a high  
881 prevalence of infectious complications and undue pill burden. Some studies suggest that peritoneal  
882 dialysis is associated with slightly better QOL than hemodialysis<sup>218</sup>, but it is possible that this  
883 observation is confounded by patient characteristics<sup>219</sup>. Home dialysis strategies are constantly  
884 improving and are becoming possible tools to improve QOL<sup>220</sup>. Kidney transplantation is associated  
885 with substantially better QOL than either form of dialysis<sup>221</sup>, but even recipients with good graft  
886 function must face CKD-related symptoms as well as complications of immunosuppression and other  
887 treatments.

888 Recent emphasis on patient-centred research should help to improve QOL for people with  
889 CKD by increasing the likelihood that important but understudied issues such as symptom control are  
890 studied and new solutions are identified. In addition, findings from patient-centred research should  
891 help to drive uptake of patient-centred care at the bedside, especially if supported by patient-  
892 reported outcomes<sup>222</sup>. Such paradigm shifts should help to prioritize the management of patient-  
893 important issues such as reduced QOL.

894  
894

## 895 [H1] Outlook

896 There are many unmet medical needs in nephrology as a specialty and improving and refining our  
897 understanding of disease mechanisms in common and rarer conditions is lacking, as are novel  
898 therapies to treat rarer and common causes of kidney disease progression and a culture of curiosity  
899 and clinical trials that advance the field<sup>37</sup>. Key areas are to improve the identification of CKD and to  
900 reduce CKD risk factors, to improve the understanding of causes and consequences of CKD, to

901 improve outcomes with current knowledge, and finally to develop and test new therapeutic  
902 strategies<sup>37</sup>. Here, we highlight eight promising domains expected to produce significant impact on  
903 CKD management and outcomes.

904904

905 **[H2]How genetic kidney disease contributes to CKD**

906 Genetic abnormalities were identified in 20% of CKD cases in children, adolescents, and young adults.  
907 Next generation sequencing have unveiled the extreme genetic heterogeneity of kidney disease. For  
908 example more than 40 different genes were discovered as possible causes of steroid-resistant  
909 nephrotic syndrome<sup>142</sup>. This requires implementation of current diagnostic strategies that go beyond  
910 th renal biopsy and open to personalized diagnosis and treatments<sup>142</sup>. In addition, first genetic  
911 modifiers of CKD progression such as *APOL1* or *UMOD* have been identified in older adults. CKD in  
912 adults may also relate to (genetically- or environmentally-defined) low nephron endowment or AKI  
913 episodes early in life, e.g. as early as during neonatal (intensive) care. Thus, CKD in adults, often  
914 classified by a single diagnosis, may often be the consequence of several components accumulating  
915 with time, a conclusion having important implications for the design of CKD trials, e.g. in prevalent  
916 entities such as “diabetic nephropathy”. Progress will require identifying the cause(s) of CKD and  
917 dissecting modifiable from non-modifiable drivers of CKD progression as well as specific  
918 pathophysiological mechanisms that might help to define more homogeneous patient subgroups.  
919 The identification of such subgroups is a prerequisite to conducting more targeted clinical trials,  
920 which require fewer participants and increase the possibility to identify appropriate drugs for  
921 different subtypes of patients. Patient heterogeneity is considered one of the main reasons why  
922 clinical trials in nephrology commonly fail<sup>223</sup>. Genetic investigations might therefore not only hold  
923 promise for individual patients, for example by facilitating the diagnosis of a monogenic disease with  
924 potential implications for individualized treatment, but might also improve classification and  
925 ultimately treatment and/or prevention in groups of patients<sup>224</sup>. The study of the genetic  
926 predisposition to kidney diseases has made major progress over the past decade. For the first time,

927 researchers have been able to carry out genome-wide screens to study complex kidney diseases, to  
928 which genetic susceptibility variants in many genes, as well as environmental factors, contribute.  
929 Genome-wide association studies (GWAS) have emerged as an important method to map risk loci for  
930 complex diseases by investigating the association of genetic markers across the genome with the  
931 disease of interest. We can predict that the list of genetic forms of CKD will exponentially increase  
932 together with our understanding of the genetic component of kidney function in health and disease  
933 933933 224.

934 934934

### 935 [H2]Biomarkers for CKD management

936 As discussed, using serum creatinine-based diagnosis implies diagnosis as late as CKD G3, leaving a  
937 small window of opportunity for modulating CKD progression. Earlier identification CKD with  
938 biomarkers that can also predict CKD progression would help to initiate nephroprotective  
939 interventions<sup>37</sup>. Most attractive would be a marker of nephron number. Defining nephron number at  
940 birth would display low nephron endowment and help to dissect it from injury- or ageing-related  
941 nephron loss later in life. A marker of nephron number would detect CKD G2 and could serve as an  
942 end point parameter for clinical trials to quantify nephro-protective effects or drug toxicity. However,  
943 identifying a clinically applicable biomarker of nephron number in serum or urine has been  
944 unsuccessful so far. Biomarkers do not clearly discriminate nephron number from the compensatory  
945 increase in mass of remnant nephrons upon injury (remnant nephron hypertrophy). Imaging studies  
946 with tracers or the combination of imaging with kidney biopsy indicating the number of glomeruli  
947 and even SNGFR are promising as a proof-of-concept<sup>85, 225</sup>.

948

### 949 [H2]Separating triggers of nephron loss from CKD progression

950 Congenital low nephron endowment, obesity, and AKI/CKD-related nephron loss imply  
951 hyperfiltration and hypertrophy of the remnant nephrons, which in turn promote secondary FSGS  
952 and further nephron loss. Interstitial fibrosis most likely represents matrix replacement of lost

953 nephrons, thereby stabilizing the remnant nephrons. Whether fibrosis itself contributes to nephron  
954 loss remains under debate and several antifibrotic drugs are under study to test this concept<sup>226, 227</sup>.  
955 Dissecting the relative contribution of nephron injury, wound healing, and compensatory  
956 hyperfiltration remains notoriously difficult in clinical practice. Finding ways to define their relative  
957 contribution and selectively target these mechanisms in a personalized manner remains a challenge  
958 for the following years.

959959

## 960 [H2] Modifying CKD progression

961 Among the many ideas on how to potentially modulate CKD progression some accumulated a large  
962 fundamant of experimental evidence but still await successful validation in human RCTs (e.g.  
963 protecting nephron loss by modulating kidney fibrosis)<sup>228</sup>. In contrast, the idea to retard CKD  
964 progression with urate-lowering therapies already showed promising results in smaller trials and the  
965 results of ongoing multicenter RCT are eagerly awaited<sup>229</sup>. In contrast, the nuclear factor (erythroid-  
966 derived 2)-like (NRF)-2 agonist bardoxolone or folic acid supplementation have shown  
967 nephroprotective effects in RCTs in some populations but their mechanisms-of-action are not yet  
968 fully understood<sup>182, 230,231</sup>.

969969

## 970 [H2] Nephrogenesis and regeneration

971 Given the significant hurdles preventing widespread use of renal transplantation, Current work is  
972 exploring whether the transfer of autologous stem (progenitor) cells, stromal cells or other cell types  
973 can support the regeneration of injured nephrons (FIG. 8). For this to be a viable option, a growing  
974 research field is trying to unravel the physiology and pathophysiology of the nephron's intrinsic  
975 capacity to regenerate.

976 Several studies have identified possible drugable targets to specifically enhance nephron  
977 regeneration with pharmacologic intervention to prevent nephron loss in AKI and CKD<sup>232</sup>. In  
978 particular, targeting parietal epithelial cells that can act as progenitor for podocytes, to promote

979 their differentiation into fully functional podocytes and/or to block their excessive proliferation and  
980 matrix production can promote remission of glomerular disorders <sup>233-235</sup>. In addition, enhancing  
981 tubular regeneration by promoting tubular epithelial cell proliferation can reduce the occurrence of  
982 CKD after AKI <sup>234, 236</sup>. Although in vivo experimental studies appear promising, no clinical trials are  
983 available yet <sup>233-235</sup>. Finally, numerous Inhibitors of maladaptive repair induced improved tissue  
984 structure and even function in experimental models of CKD. Several phase 1-2 clinical trials were  
985 started but up to now, but none progressed beyond phase 2 <sup>237</sup>. However, other new antifibrotic  
986 drugs display are currently being tested in clinical trials <sup>234, 237,238</sup>.

987 Regenerative medicine is also being explored for treatment of kidney disorders. Therapeutic  
988 properties mesenchymal stroma cells (MSC), a population of well-characterized, easily obtainable  
989 cells with effective in numerous but not all experimental models of CKD <sup>239, 240</sup>. The underlying  
990 mechanisms of action of the MSC have been extensively described and consist essentially in  
991 immunomodulatory and paracrine effects. Similarly, numerous experimental studies reported  
992 improvement of kidney function and/or structure by using injection of human renal progenitors <sup>232-</sup>  
993 <sup>236</sup>. However, the translation of preclinical studies into robust, effective, and safe patient therapies  
994 remains limited <sup>233, 234,237</sup>.

995 Finally, the generation of 3D organ-buds termed 'organoids' from human induced pluripotent stem  
996 cells and embryonic stem cells was achieved also for the kidney; these organoids consist of a variety  
997 of renal cell types in vitro that mimic organs in vivo <sup>241, 242</sup>. The organoid bears great potential in the  
998 study of human diseases in vitro, especially when combined with CRISPR/Cas9-based genome-editing  
999 <sup>243, 244</sup>. However, the complexity of kidney structure and function is yet far from being reproduced for  
1000 the purpose of clinical use for renal replacement therapy and the question if and when this will be  
1001 eventually possible is still open.

1002

1003 [H2]Animal models and RCT design

1004 Innovative approaches to better link translational research to clinical trial findings will need to start  
1005 with well-defined human genotypes and phenotypes to identify molecular targets, which may (or  
1006 may not) subsequently be validated in animal models. Selecting such animal models for validation  
1007 should be based on models that recapitulate CKD progression in humans and applying identical end  
1008 points in subsequent clinical trials. This may include mice with identical pathogenic mutations as in  
1009 human genetic kidney disease as being available for Alport syndrome, mouse models with a partial  
1010 human immune system, or eventually experimentation in pigs or primates to close gaps between  
1011 preclinical and clinical trials<sup>245, 246</sup>.

1012 In addition, trial design may be improved upon reconsidering disease definitions, avoiding  
1013 add-on designs using drugs with redundant mechanisms-of-action, preselecting patients with drug  
1014 mechanisms-related biomarkers, and of study end points that better predict CKD progression to  
1015 ESKD. For example, in order to test efficacy of the C5a receptor inhibitor avacopan in ANCA vasculitis  
1016 the CLEAR trial at first avoided the usual add-on standard of care approach and compared instead  
1017 avacopan plus low-dose steroids versus placebo plus high dose steroids on top of either  
1018 cyclophosphamide or rituximab<sup>247</sup>. This way it was proven that avacopan is effective in replacing  
1019 high-dose glucocorticoids in treating vasculitis.

1020

1021 **[H2]Limiting cardiovascular morbidity and mortality**

1022 Targeting the association of CKD with cardiovascular morbidity and mortality will require more  
1023 functional studies in animals and humans to identify molecular targets potentially suitable for  
1024 therapeutic interventions<sup>37</sup>. Controlling hyperlipidemia with PCSK9 inhibitors, suppressing systemic  
1025 inflammation with innovative anti-inflammatory drugs, modulating the intestinal microbiota, or  
1026 directly modulating vascular calcification and cardiac fibrosis may offer new solutions for this eminent  
1027 problem in the future.

1028

1029 **[H2]Translation of advances into daily practice**

1030       The ever growing complexity of kidney biopsy reading, lab diagnostics, and the increasing need for  
1031       genetic testing will require centers of excellence with sufficient resources to meet the diagnostic  
1032       demands. The same may apply to upcoming costly therapies, where patient selection is of particular  
1033       importance. Educational efforts are also needed to alert patients and general physicians to the  
1034       increasing number of more affordable therapeutic options for CKD patients with diabetes, such as  
1035       SGLT2 inhibitors. Finally, national CKD registries and treatment guidelines advocate awareness in the  
1036       public, among health care providers, and decision takers, which can generate important support for  
1037       implementation of standards<sup>37</sup>. Global guidelines created by the KDIGO initiative have become  
  
1038       instrumental in this process starting from a global definition of CKD stages up to defining standards  
1039       for the management of CKD complications (**Box 3**). In addition, global initiatives on CKD launched by  
1040       the International Society of Nephrology define knowledge gaps in CKD and propose how to address  
1041       them in the future<sup>37</sup>.  
  
1042  
  
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1049  
  
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1051       manuscript.  
  
1052

1053 **Box 1. Risk factors for chronic kidney disease**

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- 1054 • Diabetes mellitus (type 1 or 2)
- 1055 • Poorly controlled arterial hypertension
- 1056 • Obesity
- 1057 • Monogenetic kidney disease (for example, autosomal dominant polycystic kidney disease, podocytopathies causing steroid-resistant nephrotic syndrome, Fabry's disease and Alport syndrome, complementopathies such as atypical haemolytic-uremic syndrome (aHUS))
- 1058
- 1059
- 1060 • Prolonged exposure to nephrotoxins (e.g., chemotherapy for cancer treatment, proton pump inhibitors, non-steroidal anti-inflammatory drugs, and anti-microbial agents), contaminated herbs, agricultural chemicals, heavy metals, irradiation)
- 1061
- 1062
- 1063 • Climate (excessive heat exposure and dehydration)
- 1064 • Infections and chronic inflammation (HIV, HCV, HBV, malaria, bacterial infections urinary
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1076

- tract infections, rheumatic disorders and autoimmune diseases)
- Low nephron endowment at birth (low birth weight, fetal dysmaturity)
    - Obstructive uropathy
    - Systemic vasculitis
    - Hyperhomocysteinemia
  - Malignancy (especially lymphocyte and plasma cell disorders such as multiple myeloma)
  - Congenital renal abnormalities (CAKUT, vesico-ureteric reflux)
  - Episodes of acute kidney injury

1077 **Box 2. Biochemical and serologic tests useful for defining causes of CKD**

1078 **[H1]Auto-immune disease**

- 1079 • Fluorescent anti-nuclear antibody, anti-dsDNA antibody, anti-phospholipaseA2 receptor  
1080 antibody, anti-GBM antibody, anti-neutrophil cytoplasmic antibody, anti-phospholipid  
1081 antibody  
1082 • Serum hemolytic complement activity (C'H50), serum C3 and C4 levels, cryoimmunoglobulins

1083 **[H1]Malignancy**

- 1084 • Serum free light chains, serum or urinary immunofixation (multiple myeloma)  
1085 • Serum albumin, phosphorous, total proteins and albumin/globulin ratio

1086 **[H1]Infections**

- 1087 • Human Immunodeficiency Virus, hepatitis B virus, hepatitis C virus serology, CD4+ T cell  
1088 counts, urine, blood cultures, anti-streptococcal antibody tests

1089 **[H1]Monogenetic kidney disease**

- 1090 • Serum or urinary enzymes, glycolipids  
1091 • Genetic testing using next generation and Sanger sequencing

1092

1093 **Box 3. Key strategies to managing CKD complications**

1094 **[H1]Renal anemia** <sup>187</sup>

- 1095 • Erythropoiesis stimulating agents (ESAs) are only given once all correctable causes of
- 1096 anemia (e.g. iron deficiency and inflammatory states) have been addressed
- 1097 • Adults received Iron supplementation when transferrin saturation is <30% and ferritin <500
- 1098 ng/ml; children (<18 years) receive Iron supplementation when transferrin saturation is
- 1099 <20% and ferritin <100 ng/ml
- 1100 • ESAs may be used to avoid hemoglobin <9.0 g/l with a target of max.11.5 g/dl
- 1101 • Avoid blood transfusion whenever possible, especially in potential transplant recipients.
- 1102 Caution in giving ESAs in people at risk of stroke or who have malignancy

1103 **[H1]Arterial hypertension** <sup>188</sup>

- 1104 • Individualize blood pressure (BP) targets are based on age and co-morbidities, with special
- 1105 recommendations for diabetes
- 1106 • Targets include normalizing body weight (BMI 20-25), NaCl intake (<5g/d), achieving regular
- 1107 physical exercise, limiting alcohol intake to 2 drinks/d (men), 1 drink/day (women)

1108 **[H1]Mineral and bone disorder** <sup>189, 248</sup>

- 1109 • Monitor calcium, phosphorus, parathyroid hormone, and alkaline phosphatase activity in
- 1110 adults beginning in CKD G3a and in children beginning in with CKD G2 ; 25(OH)D levels
- 1111 might also be measured and corrected by vitamin D supplementation as for the general
- 1112 population
- 1113 • In CKD G3a-G5D lower elevated phosphate levels toward the normal range but avoid
- 1114 hypercalcemia by restricting the dose of calcium-based phosphate binders
- 1115 • Avoid long-term exposure to aluminium in phosphate binders or dialysate
- 1116 • Measure bone mass density in patients with CKD G3a-G5D with evidence of bone disease to
- 1117 assess fracture risk if results will impact treatmentIn adults calcitriol and vitamin D

1118           analogues are no longer recommended for routine use unless secondary

## 1119 hyperparathyroidism in CKD G4-G5 is severe and progressive

- For patients with CKD G5D PTH-lowering therapy calcimimetics, calcitriol, or vitamin D

1121 analogs are recommended

- 1122 • Consider patients with vascular calcifications at high risk for cardiovascular disease; avoid

1123 calcium-based phosphate binders in these patients, limit dietary phosphate intake.

## 1124 [H1]Hyperlipidemia 249

- Adults >50y with CKD should receive a statin; when eGFR <60ml/min, statin or

1126 statin/ezetimibe combination should be given

- Adults <50y with CKD and other cardiovascular risk factors should receive a statin

## 1128 [H1]Metabolic acidosis

- Oral bicarbonate can be used to correct mild metabolic acidosis

## 1130 [H1]Chronic hyperkalemia

- 1131 • Dietary restriction, loop diuretics, potassium-binding resins such as patiromer or dose

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1142 **Figure legends**

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1144 **Figure 1. Kidney Disease Improving Global Outcomes (KDIGO) classification of chronic kidney  
disease (CKD).** The 2D matrix illustrates the predictive value of different levels of albuminuria and  
1145 estimated glomerular filtration rate (eGFR). The color code indicates the risk for CKD progression to  
1146 end-stage kidney disease (ESKD) and overall mortality. This matrix defines different stages of CKD  
1147 referred as, for example, CKD G2A2 whereby the eGFR is 60-89 ml/min/1.73m<sup>2</sup> albuminuria is  
1148 moderately increased; such a patient would have a moderately increased risk of progressing to ESKD.  
1149 This staging system for CKD G2-G4 may underestimate the extent of irreversible nephron loss<sup>251</sup>.  
1150 That is, if total GFR relies on the single nephron GFR (SNGFR) and the number of nephrons, SNGFR  
1151 has to increase to compensate for reduced (or declining) number of nephrons to maintain total GFR.  
1152 However, such a compensation may not occur with physiological ageing<sup>85</sup>. Additionally, total GFR  
1153 drops if remnant nephrons are not able to increase SNGFR. Finally, increases in serum creatinine  
1154 levels (representing a GFR of ≤40%) may imply remnant nephrons of ≤30% of a “normal” nephron  
1155 number. Furthermore, the prognosis facet of CKD classification has been developed by large-scale  
1156 population-based epidemiological studies, which suffer from a “false positive” rate of- approximately  
1157 30-35% as in such studies repeat analysis after 3 months was often not available<sup>43</sup>. Reprinted with  
1158 permission from Kidney Disease: Improving Global Outcomes (KDIGO) CKD Work Group.  
1159 KDIGO clinical practice guideline for the evaluation and management of chronic kidney disease.  
1160 Kidney Int Suppl. 2013;3:1-150.

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1163 **Figure 2. Global prevalence of treated end-stage kidney disease per 1 million population.** The map  
1164 depicts the prevalence of renal replacement therapy represented by kidney replacement therapy  
1165 (kidney replacement therapy: hemodialysis, peritoneal dialysis, and kidney transplantation), for  
1166 [Au:OK?ok] ESKD per 1 million population based on individual country data. Data not available  
1167 indicates that data were either not known or not provided on the questionnaire for countries that

1168 received the survey. Reprinted with permission from Bello, A. K. et al. Assessment of  
1169 Global Kidney Health Care Status. JAMA 317, 1864-1881 (2017)

1170

1171 **Figure 3. Glomerular filtration rate (GFR) over time and impact of low birth weight on progression**  
1172 **of CKD.** A. Population studies assessing estimated GFR document a decline in eGFR with age; here  
1173 the data in men from Morocco are shown<sup>43</sup>. P values from P03-P97 represent the percentiles of the  
1174 entire population with P50 representing mean values. This decline is a consequence of loss of  
1175 functioning nephrons via glomerulosclerosis-related nephron atrophy and is not accompanied by a  
1176 compensatory increase in SNGFR in the remaining intact nephrons, unlike what occurs when  
1177 nephrons are lost by injury or surgery<sup>42, 52, 85</sup>. At age 70, nephron number is around 50% of that at  
1178 age 25. Whether or not this implies increased SNGFR (single nephron hyperfiltration) of remnant  
1179 nephrons or mirrors the declining demand for filtering metabolic waste is under debate but will  
1180 strongly depend on co-morbidities such as obesity and the life time history of acute kidney injury  
1181 episodes. In such cases, SNGFR should correlate with the total number of nephrons per body mass. B:  
1182 Low birth weight (LBW) increases four-fold the relative risk to develop CKD by the age 17 as shown  
1183 by population studies<sup>69</sup>. C: LBW status also significantly shortens the time span of when patients  
1184 with IgA nephropathy reach end stage kidney disease<sup>70</sup>.

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1186 **Figure 4. Contributing factors to nephron loss.** In addition to ageing, acute and chronic forms of  
1187 kidney injuries further may contribute to nephron loss along life time. Environmental, genetic causes  
1188 and systemic disease-related reasons for low nephron endowment or causes of nephron injury are  
1189 shown during the different phases in life, when they are most commonly (but not exclusively)  
1190 encountered. Combinations of such causes determine the individual risk for CKD throughout life. For  
1191 example, congenital abnormalities of the urinary tract (CAKUT) can lead to end stage kidney disease  
1192 (ESKD) early in life, or to secondary focal segmental glomerulosclerosis (FSGS)-related ESKD later in  
1193 life. Nephrotoxic drugs such as antibiotics, pain killers, contrast media for imaging or chemotherapy

1194 can also influence risk, as can infections (bacterial, parasitic, viral). Severe genetic defects that lead to  
1195 FSGS, Alport syndrome, cysts and atypical hemolytic uremic syndrome typically become evident early  
1196 in life, whereas moderate genetic defects (such as mutation in *UMOD*) can become evident in  
1197 adulthood. Genetic variants in genes such as *APOL1* can modify the course of diseases such as lupus  
1198 nephritis.

1199

1200 **Figure 5. Injury, hyperfiltration and hypertrophy of the nephron.** A | In response to nephron loss,  
1201 single nephron hyperfiltration induces an increase in nephron size as a compensatory mechanism to  
1202 maintain overall renal function. Accordingly, podocytes need to undergo hypertrophy to maintain the  
1203 filtration barrier of the increasing dimensions of the filtration surface. However, podocyte  
1204 hypertrophy is limited; beyond a certain threshold, barrier dysfunction first manifests as mild to  
1205 moderate proteinuria. At later stages the increasing podocyte shear stress promotes podocyte  
1206 detachment. Parietal epithelial cells (PEC) host putative podocyte progenitors but proteinuria and  
1207 potentially other factors inhibit their potential to replace lost podocytes and rather promote scar  
1208 formation, i.e. focal segmental glomerulosclerosis (FSGS). B | Hyperfiltration and proteinuria both  
1209 imply an increased reabsorption work load for proximal tubules. Activated tubular cells secrete pro-  
1210 inflammatory mediators that promote interstitial inflammation. Together with the progression from  
1211 FSGS to global glomerulosclerosis the inflammatory microenvironment of the tubulointerstitium  
1212 promotes tubular atrophy and interstitial fibrosis. Scar formation is associated with vascular  
1213 rarefaction and ischemia. The remnant nephrons have to further increase in size to meet the  
1214 filtration demands, which accelerates the aforementioned mechanisms of CKD progression in a  
1215 vicious circle.

1216 **Figure 6. The earlier-the-better: renal outcome depending on when starting renin-angiotensin  
1217 system (RAS) blockade in Alport Syndrome.** As shown, the time to renal replacement therapy was  
1218 longest for those who started RAS inhibition early, at onset of microhematuria (usually at birth) or  
1219 microalbuminuria (30-300 mg protein per day or per gram creatinine). Delaying until

1220 macroproteinuria (>0.3g/day or per gram creatinine (green curve)) or CKD G3/4 has been established  
1221 considerably shortens the time to renal replacement. Untreated patients (red curve) are relatives to

1222 Reprinted with permission from Gross, O. et al. Early angiotensin-converting enzyme inhibition in Alport syndrome delays renal failure and improves life expectancy. Kidney Int 81, 494-501 (2012).

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1226 **Figure 7. Access for hemodialysis or peritoneal dialysis.** A | Arteriovenous fistulae are created by  
1227 surgical anastomosis of a peripheral artery with a larger subcutaneous vein, e.g. at the forearm. The  
1228 increased flow and perfusion pressure leads to structural modifications in the draining vein allowing  
1229 repetitive venous puncture for hemodialysis. Sometimes declining blood flow to the hand and fingers  
1230 (steal phenomenon), compensatory increases in cardiac output or aneurysm formation cause  
1231 problems and require surgical correction. B | Arteriovenous grafts may become necessary when the  
1232 patient's vascular status does not allow to build a fistula. Polytetrafluoroethylene grafts are mostly  
1233 used and can be repetitively punctured for hemodialysis. Common problems are sterile inflammatory  
1234 postimplantation syndromes or prosthetic graft infections causing bacterial sepsis. C | Central  
1235 venous catheters become necessary when immediate initiation of renal replacement therapy is  
1236 needed up to when a fistula or graft implant becomes ready for use. Such catheters may remain the  
1237 last vascular access option for patients in which the vascular or cardiac status does not allow fistula  
1238 or graft placement. Catheter infections or thrombotic complications remain constant concerns.  
1239 Peritoneal dialysis requires placement of a transcutaneous catheter into the peritoneal cavity. This  
1240 catheter allows fills, drains and refills of dialysate while the peritoneum serves as exchange  
1241 membrane with the uremic blood. Fluid drains and refills with fresh dialysate are needed in regular  
1242 intervals, usually 4 times a day.

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1244 **Figure 8. Targeting kidney regeneration.** In the future, it may be possible to target kidney  
1245 regeneration and maladaptive repair to minimize the loss of injured nephrons and to protect the

1246 remnant nephrons. Here, the most promising arenas of research include: 1. Enhancing podocyte  
1247 regeneration. This aim may be achieved by drugs that promote differentiation into podocyte or  
1248 parietal epithelial cell (PEC) progenitors of the Bowman's capsule and/or blocking their excessive  
1249 proliferation. 2. Blocking fibrosis and/or maladaptive repair by inhibiting fibroblast expansion. 3.  
1250 Enhancing tubular regeneration by blocking maladaptive repair and/or enhancing tubular cell  
1251 proliferation<sup>233-238</sup>.

1252

1253 **Figure 9. Cell therapy and organoids as potential tools in CKD research and therapy.** (A) Injection of  
1254 two cell types, mesenchymal stromal cells and renal progenitors, were reported as possible tools for  
1255 cell therapy of CKD, improving kidney function and structure in animal models. Numerous phase 1-2  
1256 clinical trials are ongoing. Several mechanisms were proposed to explain the beneficial effects  
1257 observed, mostly based on secretion of paracrine factors and/or microvesicles. For renal progenitors  
1258 also direct engraftment in the injured tissue was reported. (B) Kidney organoids were generated in  
1259 vitro starting from induced pluripotent stem cells (iPSC) and embryonic stem cells (ESC) and used for  
1260 testing of drug toxicity and modeling of kidney diseases, with or without manipulation using  
1261 Crispr/Cas and other genome editing strategies.

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**Table 1. Therapeutic interventions for selected conditions associated with CKD risk**

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Disease entity	Diagnostic test	Therapeutic interventions
<b><i>Genetic injury</i></b>		
Polycystic kidney disease	Echography or MRI to detect cysts	Tolvaptan (vasopressin receptor 2 antagonist of benefit in selected patients)
Alport syndrome	Genetic testing for collagen mutations	ACE inhibitors to reduce filtration pressure in remnant nephrons
Fabry disease	Serum alpha-galactosidase activity	Alpha-galactosidase replacement therapy
Primary hyperoxaluria	Echography to detect nephrocalcinosis, urinary oxalate levels, genetic testing for serine—pyruvate aminotransferase , glyoxylate reductase/hydroxypyruvate reductase, and dihydropyridine synthase-like	Increase fluid intake, supplementation with potassium citrate, magnesium oxide, pyridoxine , and orthophosphate, oxalate-reduced diet, liver transplantation
Cystinosis	Leukocyte cystine levels, slit lamp exam of the eyes, genetic testing for the cystinosin gene	Cysteamine substitution
Coenzyme Q10-related gene mutations causing FSGS	Genetic testing for AarF Domain Containing Kinase-4, coenzyme Q2, coenzyme Q6, and decaprenyl diphosphate synthase subunit 2	Coenzyme Q10 replacement therapy
C3 glomerulonephritis	Kidney biopsy, specific complement test, genetic testing for complement-related genes	Plasma exchange or blood transfusion, rituximab, eculizumab (depending on specific cause)
<b><i>Immune injury</i></b>		
Acute or subacute immune complex glomerulonephritis	Autoantibodies against nuclear autoantigens or neutrophil cytoplasmic antigens such as proteinase 3 or myeloperoxidase,	Immunosuppressive drugs, plasma exchange (in certain settings)

	C3/C4 serum levels urinary sediment, kidney biopsy	
Renal vasculitis	ANCA, urinary sediment, kidney biopsy	Immunosuppressive drugs, plasma exchange (in certain settings)
<b>Vascular injury</b>		
Recent onset renal artery stenosis (fibromuscular or vasculitic)	Angiogram of the renal arteries	Surgical revascularization or catheter-based angioplasty
<b>Metabolic injury</b>		
Diabetic kidney disease	Blood glucose level, albuminuria, kidney biopsy	Antidiabetic drugs, SGLT2 blockade, RAS inhibitors
Chronic urate nephropathy	Tophaceous gout, serum uric acid levels, kidney biopsy	Purine-reduced diet, uricosuric drugs, xanthine oxidase inhibitors, rasburicase
<b>Toxic injury</b>		
Toxic nephropathies (lead, aristolochic acid, phenacetin, ...)	History, specific toxin levels, kidney biopsy	Abandon toxin exposure
Multiple myeloma	Serum or urinary free light chain test, bone marrow aspirate, kidney biopsy	Myeloma-directed chemotherapy
<b>Kidney infections</b>		
Bacterial pyelonephritis	Urine culture	Increased fluid intake, antibiotics
Viral nephropathies	Viral testing, kidney biopsy	Antiviral therapy
<b>Mechanical injury</b>		
Obstructive nephropathy	Renal ultrasound	Relieve obstruction

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1281 **References**

- 1282 1. Kidney Disease: Improving Global Outcomes (KDIGO) CKD Work Group. KDIGO clinical  
1283 practice guideline for the evaluation and management of chronic kidney disease. *Kidney Int Suppl* **3**, 1-150 (2013).
- 1284 2. Glasscock, R., Delanaye, P. & El Nahas, M. An Age-Calibrated Classification of Chronic Kidney  
1285 Disease. *JAMA* **314**, 559-60 (2015).
- 1286 3. Levey, A.S., Inker, L.A. & Coresh, J. Chronic Kidney Disease in Older People. *JAMA* **314**, 557-8  
1287 (2015).
- 1288 4. Poggio, E.D. et al. Demographic and clinical characteristics associated with glomerular  
1289 filtration rates in living kidney donors. *Kidney Int* **75**, 1079-87 (2009).
- 1290 5. Pottel, H., Hoste, L., Yayo, E. & Delanaye, P. Glomerular Filtration Rate in Healthy Living  
1291 Potential Kidney Donors: A Meta-Analysis Supporting the Construction of the Full Age  
1292 Spectrum Equation. *Nephron* **135**, 105-119 (2017).
- 1293 6. Glasscock, R.J. & Rule, A.D. The implications of anatomical and functional changes of the aging  
1294 kidney: with an emphasis on the glomeruli. *Kidney Int* **82**, 270-7 (2012).
- 1295 7. Hallan, S.I. et al. Age and association of kidney measures with mortality and end-stage renal  
1296 disease. *JAMA* **308**, 2349-60 (2012).
- 1297 8. Warnock, D.G., Delanaye, P. & Glasscock, R.J. Risks for All-Cause Mortality: Stratified by Age,  
1298 Estimated Glomerular Filtration Rate and Albuminuria. *Nephron* (2017).
- 1299 9. De Broe, M.E., Gharbi, M.B., Zamd, M. & Elseviers, M. Why overestimate or underestimate  
1300 chronic kidney disease when correct estimation is possible? *Nephrol Dial Transplant* **32**,  
1301 ii136-ii141 (2017).
- 1302 10. Denic, A., Glasscock, R.J. & Rule, A.D. Structural and Functional Changes With the Aging  
1303 Kidney. *Adv Chronic Kidney Dis* **23**, 19-28 (2016).
- 1304 11. DALYs, G.B.D. & Collaborators, H. Global, regional, and national disability-adjusted life-years  
1305 (DALYs) for 315 diseases and injuries and healthy life expectancy (HALE), 1990-2015: a  
1306 systematic analysis for the Global Burden of Disease Study 2015. *Lancet* **388**, 1603-1658  
1307 (2016).
- 1308 12. Jager, K.J. & Fraser, S.D.S. The ascending rank of chronic kidney disease in the global burden  
1309 of disease study. *Nephrol Dial Transplant* **32**, ii121-ii128 (2017).
- 1310 13. Mortality, G.B.D. & Causes of Death, C. Global, regional, and national age-sex specific all-  
1311 cause and cause-specific mortality for 240 causes of death, 1990-2013: a systematic analysis  
1312 for the Global Burden of Disease Study 2013. *Lancet* **385**, 117-71 (2015).
- 1313 14. Thomas, B. et al. Global Cardiovascular and Renal Outcomes of Reduced GFR. *J Am Soc  
1314 Nephrol* **28**, 2167-2179 (2017).
- 1315 15. Zhang, L. et al. Prevalence of chronic kidney disease in China: a cross-sectional survey. *Lancet*  
1316 **379**, 815-22 (2012).
- 1317 16. Arora, P. et al. Prevalence estimates of chronic kidney disease in Canada: results of a  
1318 nationally representative survey. *CMAJ* **185**, E417-23 (2013).
- 1319 17. White, S.L., Polkinghorne, K.R., Atkins, R.C. & Chadban, S.J. Comparison of the prevalence  
1320 and mortality risk of CKD in Australia using the CKD Epidemiology Collaboration (CKD-EPI)  
1321 and Modification of Diet in Renal Disease (MDRD) Study GFR estimating equations: the  
1322 AusDiab (Australian Diabetes, Obesity and Lifestyle) Study. *Am J Kidney Dis* **55**, 660-70  
1323 (2010).
- 1324 18. Levey, A.S. & Coresh, J. Chronic kidney disease. *Lancet* **379**, 165-80 (2012).
- 1325 19. Girndt, M., Trocchi, P., Scheidt-Nave, C., Markau, S. & Stang, A. The Prevalence of Renal  
1326 Failure. Results from the German Health Interview and Examination Survey for Adults, 2008-  
1327 2011 (DEGSS1). *Dtsch Arztebl Int* **113**, 85-91 (2016).
- 1328 20. Bruck, K. et al. CKD Prevalence Varies across the European General Population. *J Am Soc  
1329 Nephrol* **27**, 2135-47 (2016).

- 1331 21. Fraser, S.D. et al. Exploration of chronic kidney disease prevalence estimates using new  
1332 measures of kidney function in the health survey for England. *PLoS One* **10**, e0118676 (2015).
- 1333 22. Glasscock, R.J., Warnock, D.G. & Delanaye, P. The global burden of chronic kidney disease:  
1334 estimates, variability and pitfalls. *Nat Rev Nephrol* **13**, 104-114 (2017).
- 1335 23. Stanifer, J.W., Muiru, A., Jafar, T.H. & Patel, U.D. Chronic kidney disease in low- and middle-  
1336 income countries. *Nephrol Dial Transplant* **31**, 868-74 (2016).
- 1337 24. Stanifer, J.W. et al. The epidemiology of chronic kidney disease in sub-Saharan Africa: a  
1338 systematic review and meta-analysis. *Lancet Glob Health* **2**, e174-81 (2014).
- 1339 25. Ene-Iordache, B. et al. Chronic kidney disease and cardiovascular risk in six regions of the  
1340 world (ISN-KDDC): a cross-sectional study. *Lancet Glob Health* **4**, e307-19 (2016).
- 1341 26. Hill, N.R. et al. Global Prevalence of Chronic Kidney Disease - A Systematic Review and Meta-  
1342 Analysis. *PLoS One* **11**, e0158765 (2016).
- 1343 27. Jha, V. et al. Chronic kidney disease: global dimension and perspectives. *Lancet* **382**, 260-72  
1344 (2013).
- 1345 28. Charlton, J.R., Springsteen, C.H. & Carmody, J.B. Nephron number and its determinants in  
1346 early life: a primer. *Pediatr Nephrol* **29**, 2299-308 (2014).
- 1347 29. Khalsa, D.D., Beydoun, H.A. & Carmody, J.B. Prevalence of chronic kidney disease risk factors  
1348 among low birth weight adolescents. *Pediatr Nephrol* **31**, 1509-16 (2016).
- 1349 30. Gifford, F.J., Gifford, R.M., Eddleston, M. & Dhaun, N. Endemic Nephropathy Around the  
1350 World. *Kidney Int Rep* **2**, 282-292 (2017).
- 1351 31. Glaser, J. et al. Climate Change and the Emergent Epidemic of CKD from Heat Stress in Rural  
1352 Communities: The Case for Heat Stress Nephropathy. *Clin J Am Soc Nephrol* **11**, 1472-83  
1353 (2016).
- 1354 32. Jayasumana, C. et al. Chronic interstitial nephritis in agricultural communities: a worldwide  
1355 epidemic with social, occupational and environmental determinants. *Nephrol Dial Transplant*  
1356 **32**, 234-241 (2017).
- 1357 33. ESPN/ERA-EDTA Registry. Annual Report. [www.espn-reg.org/index.jsp](http://www.espn-reg.org/index.jsp) (last accessed April  
1358 2017). (2014).
- 1359 34. Chesnaye, N. et al. Demographics of paediatric renal replacement therapy in Europe: a report  
1360 of the ESPN/ERA-EDTA registry. *Pediatr Nephrol* **29**, 2403-10 (2014).
- 1361 35. Saran, R. et al. US Renal Data System 2016 Annual Data Report: Epidemiology of Kidney  
1362 Disease in the United States. *Am J Kidney Dis* **69**, A7-A8 (2017).
- 1363 36. Harambat, J., van Stralen, K.J., Kim, J.J. & Tizard, E.J. Epidemiology of chronic kidney disease  
1364 in children. *Pediatr Nephrol* **27**, 363-73 (2012).
- 1365 37. Levin, A. et al. Global kidney health 2017 and beyond: a roadmap for closing gaps in care,  
1366 research, and policy. *Lancet* (2017).
- 1367 38. Bello, A.K. et al. Assessment of Global Kidney Health Care Status. *JAMA* **317**, 1864-1881  
1368 (2017).
- 1369 39. Liyanage, T. et al. Worldwide access to treatment for end-stage kidney disease: a systematic  
1370 review. *Lancet* **385**, 1975-82 (2015).
- 1371 40. Bertram, J.F., Douglas-Denton, R.N., Diouf, B., Hughson, M.D. & Hoy, W.E. Human nephron  
1372 number: implications for health and disease. *Pediatr Nephrol* **26**, 1529-33 (2011).
- 1373 41. Brenner, B.M., Meyer, T.W. & Hostetter, T.H. Dietary protein intake and the progressive  
1374 nature of kidney disease: the role of hemodynamically mediated glomerular injury in the  
1375 pathogenesis of progressive glomerular sclerosis in aging, renal ablation, and intrinsic renal  
1376 disease. *N Engl J Med* **307**, 652-9 (1982).
- 1377 42. Hostetter, T.H., Olson, J.L., Rennke, H.G., Venkatachalam, M.A. & Brenner, B.M.  
1378 Hyperfiltration in remnant nephrons: a potentially adverse response to renal ablation. *Am J  
1379 Physiol* **241**, F85-93 (1981).
- 1380 43. Benghanem Gharbi, M. et al. Chronic kidney disease, hypertension, diabetes, and obesity in  
1381 the adult population of Morocco: how to avoid "over"- and "under"-diagnosis of CKD. *Kidney  
1382 Int* **89**, 1363-71 (2016).

- 1383           44. Ruggenenti, P., Cravedi, P. & Remuzzi, G. Mechanisms and treatment of CKD. *J Am Soc Nephrol* **23**, 1917-28 (2012).
- 1384           45. Laouari, D. et al. TGF-alpha mediates genetic susceptibility to chronic kidney disease. *J Am Soc Nephrol* **22**, 327-35 (2011).
- 1385           46. Helal, I., Fick-Brosnahan, G.M., Reed-Gitomer, B. & Schrier, R.W. Glomerular hyperfiltration: definitions, mechanisms and clinical implications. *Nat Rev Nephrol* **8**, 293-300 (2012).
- 1386           47. Grams, M.E. et al. Kidney-Failure Risk Projection for the Living Kidney-Donor Candidate. *N Engl J Med* **374**, 411-21 (2016).
- 1387           48. Mueller, T.F. & Luyckx, V.A. The natural history of residual renal function in transplant donors. *J Am Soc Nephrol* **23**, 1462-6 (2012).
- 1388           49. D'Agati, V.D. et al. Obesity-related glomerulopathy: clinical and pathologic characteristics and pathogenesis. *Nat Rev Nephrol* **12**, 453-71 (2016).
- 1389           50. Park, S. et al. Midterm eGFR and Adverse Pregnancy Outcomes: The Clinical Significance of Gestational Hyperfiltration. *Clin J Am Soc Nephrol* (2017).
- 1390           51. Tonneijck, L. et al. Glomerular Hyperfiltration in Diabetes: Mechanisms, Clinical Significance, and Treatment. *J Am Soc Nephrol* **28**, 1023-1039 (2017).
- 1391           52. Denic, A. et al. The Substantial Loss of Nephrons in Healthy Human Kidneys with Aging. *J Am Soc Nephrol* **28**, 313-320 (2017).
- 1392           53. Hodgin, J.B. et al. Glomerular Aging and Focal Global Glomerulosclerosis: A Podometric Perspective. *J Am Soc Nephrol* **26**, 3162-78 (2015).
- 1393           54. Kriz, W. & Lemley, K.V. The role of the podocyte in glomerulosclerosis. *Curr Opin Nephrol Hypertens* **8**, 489-97 (1999).
- 1394           55. Kriz, W. & Lemley, K.V. A potential role for mechanical forces in the detachment of podocytes and the progression of CKD. *J Am Soc Nephrol* **26**, 258-69 (2015).
- 1395           56. Benigni, A., Gagliardini, E. & Remuzzi, G. Changes in glomerular perm-selectivity induced by angiotensin II imply podocyte dysfunction and slit diaphragm protein rearrangement. *Semin Nephrol* **24**, 131-40 (2004).
- 1396           57. Rizzo, P. et al. Nature and mediators of parietal epithelial cell activation in glomerulonephritides of human and rat. *Am J Pathol* **183**, 1769-78 (2013).
- 1397           58. Abbate, M. et al. Transforming growth factor-beta1 is up-regulated by podocytes in response to excess intraglomerular passage of proteins: a central pathway in progressive glomerulosclerosis. *Am J Pathol* **161**, 2179-93 (2002).
- 1398           59. Abbate, M., Zoja, C. & Remuzzi, G. How does proteinuria cause progressive renal damage? *J Am Soc Nephrol* **17**, 2974-84 (2006).
- 1399           60. Peired, A. et al. Proteinuria impairs podocyte regeneration by sequestering retinoic acid. *J Am Soc Nephrol* **24**, 1756-68 (2013).
- 1400           61. Smeets, B. et al. Parietal epithelial cells participate in the formation of sclerotic lesions in focal segmental glomerulosclerosis. *J Am Soc Nephrol* **22**, 1262-74 (2011).
- 1401           62. Schnaper, H.W. The Tubulointerstitial Pathophysiology of Progressive Kidney Disease. *Adv Chronic Kidney Dis* **24**, 107-116 (2017).
- 1402           63. Kaissling, B., Lehir, M. & Kriz, W. Renal epithelial injury and fibrosis. *Biochim Biophys Acta* **1832**, 931-9 (2013).
- 1403           64. Brenner, B.M., Garcia, D.L. & Anderson, S. Glomeruli and blood pressure. Less of one, more the other? *Am J Hypertens* **1**, 335-47 (1988).
- 1404           65. de Jong, F., Monuteaux, M.C., van Elburg, R.M., Gillman, M.W. & Belfort, M.B. Systematic review and meta-analysis of preterm birth and later systolic blood pressure. *Hypertension* **59**, 226-34 (2012).
- 1405           66. Low Birth, W. & Nephron Number Working, G. The Impact of Kidney Development on the Life Course: A Consensus Document for Action. *Nephron* **136**, 3-49 (2017).
- 1406           67. Luyckx, V.A. & Brenner, B.M. Birth weight, malnutrition and kidney-associated outcomes--a global concern. *Nat Rev Nephrol* **11**, 135-49 (2015).

- 1434 68. White, S.L. et al. Is low birth weight an antecedent of CKD in later life? A systematic review of  
1435 observational studies. *Am J Kidney Dis* **54**, 248-61 (2009).
- 1436 69. Hirano, D. et al. Association between low birth weight and childhood-onset chronic kidney  
1437 disease in Japan: a combined analysis of a nationwide survey for paediatric chronic kidney  
1438 disease and the National Vital Statistics Report. *Nephrol Dial Transplant* **31**, 1895-1900  
1439 (2016).
- 1440 70. Ruggajo, P. et al. Low Birth Weight and Risk of Progression to End Stage Renal Disease in IgA  
1441 Nephropathy--A Retrospective Registry-Based Cohort Study. *PLoS One* **11**, e0153819 (2016).
- 1442 71. Becherucci, F., Roperto, R.M., Materassi, M. & Romagnani, P. Chronic kidney disease in  
1443 children. *Clin Kidney J* **9**, 583-91 (2016).
- 1444 72. Luyckx, V.A. et al. A developmental approach to the prevention of hypertension and kidney  
1445 disease: a report from the Low Birth Weight and Nephron Number Working Group. *Lancet*  
1446 (2017).
- 1447 73. Keller, G., Zimmer, G., Mall, G., Ritz, E. & Amann, K. Nephron number in patients with  
1448 primary hypertension. *N Engl J Med* **348**, 101-8 (2003).
- 1449 74. Nicolaou, N., Renkema, K.Y., Bongers, E.M., Giles, R.H. & Knoers, N.V. Genetic,  
1450 environmental, and epigenetic factors involved in CAKUT. *Nat Rev Nephrol* **11**, 720-31 (2015).
- 1451 75. Cain, J.E., Di Giovanni, V., Smeeton, J. & Rosenblum, N.D. Genetics of renal hypoplasia:  
1452 insights into the mechanisms controlling nephron endowment. *Pediatr Res* **68**, 91-8 (2010).
- 1453 76. Uy, N. & Reidy, K. Developmental Genetics and Congenital Anomalies of the Kidney and  
1454 Urinary Tract. *J Pediatr Genet* **5**, 51-60 (2016).
- 1455 77. Vivante, A. & Hildebrandt, F. Exploring the genetic basis of early-onset chronic kidney  
1456 disease. *Nat Rev Nephrol* **12**, 133-46 (2016).
- 1457 78. Eckardt, K.U. et al. Autosomal dominant tubulointerstitial kidney disease: diagnosis,  
1458 classification, and management--A KDIGO consensus report. *Kidney Int* **88**, 676-83 (2015).
- 1459 79. Kottgen, A. et al. Multiple loci associated with indices of renal function and chronic kidney  
1460 disease. *Nat Genet* **41**, 712-7 (2009).
- 1461 80. Reznichenko, A. et al. UMOD as a susceptibility gene for end-stage renal disease. *BMC Med  
1462 Genet* **13**, 78 (2012).
- 1463 81. Trudu, M. et al. Common noncoding UMOD gene variants induce salt-sensitive hypertension  
1464 and kidney damage by increasing uromodulin expression. *Nat Med* **19**, 1655-60 (2013).
- 1465 82. Dummer, P.D. et al. APOL1 Kidney Disease Risk Variants: An Evolving Landscape. *Semin  
1466 Nephrol* **35**, 222-36 (2015).
- 1467 83. Kruzel-Davila, E. et al. APOL1-Mediated Cell Injury Involves Disruption of Conserved  
1468 Trafficking Processes. *J Am Soc Nephrol* **28**, 1117-1130 (2017).
- 1469 84. Beckerman, P. et al. Transgenic expression of human APOL1 risk variants in podocytes  
1470 induces kidney disease in mice. *Nat Med* **23**, 429-438 (2017).
- 1471 85. Denic, A. et al. Single-Nephron Glomerular Filtration Rate in Healthy Adults. *N Engl J Med*  
1472 **376**, 2349-2357 (2017).
- 1473 86. Lu, J.L. et al. Association of age and BMI with kidney function and mortality: a cohort study.  
1474 *Lancet Diabetes Endocrinol* **3**, 704-14 (2015).
- 1475 87. Kramer, H. et al. Waist Circumference, Body Mass Index, and ESRD in the REGARDS (Reasons  
1476 for Geographic and Racial Differences in Stroke) Study. *Am J Kidney Dis* **67**, 62-9 (2016).
- 1477 88. Chang, A. et al. Lifestyle-related factors, obesity, and incident microalbuminuria: the CARDIA  
1478 (Coronary Artery Risk Development in Young Adults) study. *Am J Kidney Dis* **62**, 267-75  
1479 (2013).
- 1480 89. Ejerblad, E. et al. Obesity and risk for chronic renal failure. *J Am Soc Nephrol* **17**, 1695-702  
1481 (2006).
- 1482 90. Foster, M.C. et al. Overweight, obesity, and the development of stage 3 CKD: the  
1483 Framingham Heart Study. *Am J Kidney Dis* **52**, 39-48 (2008).
- 1484 91. Vivante, A. et al. Body mass index in 1.2 million adolescents and risk for end-stage renal  
1485 disease. *Arch Intern Med* **172**, 1644-50 (2012).

- 1486 92. Dunlop, W. Serial changes in renal haemodynamics during normal human pregnancy. *Br J Obstet Gynaecol* **88**, 1-9 (1981).
- 1487 93. Moran, P., Baylis, P.H., Lindheimer, M.D. & Davison, J.M. Glomerular ultrafiltration in normal and preeclamptic pregnancy. *J Am Soc Nephrol* **14**, 648-52 (2003).
- 1488 94. Anders, H.J., Davis, J.M. & Thurau, K. Nephron Protection in Diabetic Kidney Disease. *N Engl J Med* **375**, 2096-2098 (2016).
- 1489 95. Vallon, V. The mechanisms and therapeutic potential of SGLT2 inhibitors in diabetes mellitus. *Annu Rev Med* **66**, 255-70 (2015).
- 1490 96. van Bommel, E.J. et al. SGLT2 Inhibition in the Diabetic Kidney-From Mechanisms to Clinical Outcome. *Clin J Am Soc Nephrol* **12**, 700-710 (2017).
- 1491 97. Anguiano Gomez, L., Lei, Y., Devarapu, S.K. & Anders, H.J. The diabetes pandemic suggests unmet needs for 'CKD with diabetes' in addition to 'diabetic nephropathy'. Implications for pre-clinical research and drug testing. *Nephrol Dial Transplant* **in press** (2017).
- 1492 98. Wanner, C. et al. Empagliflozin and Progression of Kidney Disease in Type 2 Diabetes. *N Engl J Med* **375**, 323-34 (2016).
- 1493 99. Bellomo, R., Kellum, J.A. & Ronco, C. Acute kidney injury. *Lancet* **380**, 756-66 (2012).
- 1500 100. Venkatachalam, M.A., Weinberg, J.M., Kriz, W. & Bidani, A.K. Failed Tubule Recovery, AKI-CKD Transition, and Kidney Disease Progression. *J Am Soc Nephrol* **26**, 1765-76 (2015).
- 1501 101. Barton, A.L., Mallard, A.S. & Parry, R.G. One Year's Observational Study of Acute Kidney Injury Incidence in Primary Care; Frequency of Follow-Up Serum Creatinine and Mortality Risk. *Nephron* **130**, 175-81 (2015).
- 1502 102. Eckardt, K.U. et al. Evolving importance of kidney disease: from subspecialty to global health burden. *Lancet* **382**, 158-69 (2013).
- 1503 103. Lasagni, L., Lazzeri, E., Shankland, S.J., Anders, H.J. & Romagnani, P. Podocyte mitosis - a catastrophe. *Curr Mol Med* **13**, 13-23 (2013).
- 1504 104. Liapis, H., Romagnani, P. & Anders, H.J. New insights into the pathology of podocyte loss: mitotic catastrophe. *Am J Pathol* **183**, 1364-74 (2013).
- 1505 105. Portale, A.A. et al. Disordered FGF23 and mineral metabolism in children with CKD. *Clin J Am Soc Nephrol* **9**, 344-53 (2014).
- 1506 106. Denburg, M.R. et al. Fracture Burden and Risk Factors in Childhood CKD: Results from the CKiD Cohort Study. *J Am Soc Nephrol* **27**, 543-50 (2016).
- 1507 107. Flynn, J.T. et al. Blood pressure in children with chronic kidney disease: a report from the Chronic Kidney Disease in Children study. *Hypertension* **52**, 631-7 (2008).
- 1508 108. Foley, R.N., Parfrey, P.S. & Sarnak, M.J. Clinical epidemiology of cardiovascular disease in chronic renal disease. *Am J Kidney Dis* **32**, S112-9 (1998).
- 1509 109. Raschenberger, J. et al. Association of relative telomere length with cardiovascular disease in a large chronic kidney disease cohort: the GCKD study. *Atherosclerosis* **242**, 529-34 (2015).
- 1510 110. Grabner, A. et al. Activation of Cardiac Fibroblast Growth Factor Receptor 4 Causes Left Ventricular Hypertrophy. *Cell Metab* **22**, 1020-32 (2015).
- 1511 111. de Jager, D.J. et al. Cardiovascular and noncardiovascular mortality among patients starting dialysis. *JAMA* **302**, 1782-9 (2009).
- 1512 112. De Cosmo, S., Menzaghi, C., Prudente, S. & Trischitta, V. Role of insulin resistance in kidney dysfunction: insights into the mechanism and epidemiological evidence. *Nephrol Dial Transplant* **28**, 29-36 (2013).
- 1513 113. Cozzolino, M., Ketteler, M. & Zehnder, D. The vitamin D system: a crosstalk between the heart and kidney. *Eur J Heart Fail* **12**, 1031-41 (2010).
- 1514 114. Vervloet, M. & Cozzolino, M. Vascular calcification in chronic kidney disease: different bricks in the wall? *Kidney Int* **91**, 808-817 (2017).
- 1515 115. Carrero, J.J. et al. Etiology of the protein-energy wasting syndrome in chronic kidney disease: a consensus statement from the International Society of Renal Nutrition and Metabolism (ISRNM). *J Ren Nutr* **23**, 77-90 (2013).

- 1537 116. Massy, Z.A., Metzinger-Le Meuth, V. & Metzinger, L. MicroRNAs Are Associated with Uremic  
1538 Toxicity, Cardiovascular Calcification, and Disease. *Contrib Nephrol* **189**, 160-168 (2017).
- 1539 117. Buglioni, A. & Burnett, J.C., Jr. Pathophysiology and the cardiorenal connection in heart  
1540 failure. Circulating hormones: biomarkers or mediators. *Clin Chim Acta* **443**, 3-8 (2015).
- 1541 118. Buchanan, C. et al. Intradialytic Cardiac Magnetic Resonance Imaging to Assess  
1542 Cardiovascular Responses in a Short-Term Trial of Hemodiafiltration and Hemodialysis. *J Am  
1543 Soc Nephrol* **28**, 1269-1277 (2017).
- 1544 119. van der Heijden, B.J., van Dijk, P.C., Verrier-Jones, K., Jager, K.J. & Briggs, J.D. Renal  
1545 replacement therapy in children: data from 12 registries in Europe. *Pediatr Nephrol* **19**, 213-  
1546 21 (2004).
- 1547 120. Tonshoff, B., Kiepe, D. & Ciarmatori, S. Growth hormone/insulin-like growth factor system in  
1548 children with chronic renal failure. *Pediatr Nephrol* **20**, 279-89 (2005).
- 1549 121. Rule, A.D. et al. For estimating creatinine clearance measuring muscle mass gives better  
1550 results than those based on demographics. *Kidney Int* **75**, 1071-8 (2009).
- 1551 122. Rule, A.D. & Glasscock, R.J. GFR estimating equations: getting closer to the truth? *Clin J Am  
1552 Soc Nephrol* **8**, 1414-20 (2013).
- 1553 123. Stevens, L.A. et al. Factors other than glomerular filtration rate affect serum cystatin C levels.  
1554 *Kidney Int* **75**, 652-60 (2009).
- 1555 124. Inker, L.A. et al. Performance of glomerular filtration rate estimating equations in a  
1556 community-based sample of Blacks and Whites: the multiethnic study of atherosclerosis.  
1557 *Nephrol Dial Transplant* (2017).
- 1558 125. Praditpornsilpa, K. et al. The need for robust validation for MDRD-based glomerular filtration  
1559 rate estimation in various CKD populations. *Nephrol Dial Transplant* **26**, 2780-5 (2011).
- 1560 126. Inker, L.A. et al. Estimating glomerular filtration rate from serum creatinine and cystatin C. *N  
1561 Engl J Med* **367**, 20-9 (2012).
- 1562 127. Pottel, H. et al. An estimated glomerular filtration rate equation for the full age spectrum.  
1563 *Nephrol Dial Transplant* **31**, 798-806 (2016).
- 1564 128. Delanaye, P. et al. Iohexol plasma clearance for measuring glomerular filtration rate in clinical  
1565 practice and research: a review. Part 1: How to measure glomerular filtration rate with  
1566 iohexol? *Clin Kidney J* **9**, 682-99 (2016).
- 1567 129. Delanaye, P. et al. Iohexol plasma clearance for measuring glomerular filtration rate in clinical  
1568 practice and research: a review. Part 2: Why to measure glomerular filtration rate with  
1569 iohexol? *Clin Kidney J* **9**, 700-4 (2016).
- 1570 130. Hommos, M.S., Glasscock, R.J. & Rule, A.D. Structural and functional changes in human  
1571 kidneys with healthy aging. *J Am Soc Nephrol* (2017).
- 1572 131. Matsushita, K. et al. Estimated glomerular filtration rate and albuminuria for prediction of  
1573 cardiovascular outcomes: a collaborative meta-analysis of individual participant data. *Lancet  
1574 Diabetes Endocrinol* **3**, 514-25 (2015).
- 1575 132. Fotheringham, J., Campbell, M.J., Fogarty, D.G., El Nahas, M. & Ellam, T. Estimated albumin  
1576 excretion rate versus urine albumin-creatinine ratio for the estimation of measured albumin  
1577 excretion rate: derivation and validation of an estimated albumin excretion rate equation.  
1578 *Am J Kidney Dis* **63**, 405-14 (2014).
- 1579 133. Glasscock, R.J. Evaluation of proteinuria redux. *Kidney Int* **90**, 938-940 (2016).
- 1580 134. Azurmendi, P.J. et al. Early renal and vascular changes in ADPKD patients with low-grade  
1581 albumin excretion and normal renal function. *Nephrol Dial Transplant* **24**, 2458-63 (2009).
- 1582 135. Clark, W.F. et al. Dipstick proteinuria as a screening strategy to identify rapid renal decline. *J  
1583 Am Soc Nephrol* **22**, 1729-36 (2011).
- 1584 136. Glasscock, R.J., Fervenza, F.C., Hebert, L. & Cameron, J.S. Nephrotic syndrome redux. *Nephrol  
1585 Dial Transplant* **30**, 12-7 (2015).
- 1586 137. Glasscock, R.J. Con: kidney biopsy: an irreplaceable tool for patient management in  
1587 nephrology. *Nephrol Dial Transplant* **30**, 528-31 (2015).

- 1588 138. Jin, B. et al. The spectrum of biopsy-proven kidney diseases in elderly Chinese patients.  
1589 *Nephrol Dial Transplant* **29**, 2251-9 (2014).
- 1590 139. Xu, D.M., Chen, M., Zhou, F.D. & Zhao, M.H. Risk Factors for Severe Bleeding Complications in  
1591 Percutaneous Renal Biopsy. *Am J Med Sci* **353**, 230-235 (2017).
- 1592 140. Siwy, J. et al. Noninvasive diagnosis of chronic kidney diseases using urinary proteome  
1593 analysis. *Nephrol Dial Transplant* (2016).
- 1594 141. Li, J., An, C., Kang, L., Mitch, W.E. & Wang, Y. Recent Advances in Magnetic Resonance  
1595 Imaging Assessment of Renal Fibrosis. *Adv Chronic Kidney Dis* **24**, 150-153 (2017).
- 1596 142. Becherucci, F. et al. Lessons from genetics: is it time to revise the therapeutic approach to  
1597 children with steroid-resistant nephrotic syndrome? *J Nephrol* **29**, 543-50 (2016).
- 1598 143. Peralta, C.A. & Estrella, M.M. Preventive nephrology in the era of "I" evidence: should we  
1599 screen for chronic kidney disease? *Kidney Int* **92**, 19-21 (2017).
- 1600 144. Taal, M.W. Screening for chronic kidney disease: preventing harm or harming the healthy?  
1601 *PLoS Med* **9**, e1001345 (2012).
- 1602 145. Moyer, V.A. & Force, U.S.P.S.T. Screening for chronic kidney disease: U.S. Preventive Services  
1603 Task Force recommendation statement. *Ann Intern Med* **157**, 567-70 (2012).
- 1604 146. Fink, H.A. et al. Screening for, monitoring, and treatment of chronic kidney disease stages 1  
1605 to 3: a systematic review for the U.S. Preventive Services Task Force and for an American  
1606 College of Physicians Clinical Practice Guideline. *Ann Intern Med* **156**, 570-81 (2012).
- 1607 147. Caley, M., Chohan, P., Hooper, J. & Wright, N. The impact of NHS Health Checks on the  
1608 prevalence of disease in general practices: a controlled study. *Br J Gen Pract* **64**, e516-21  
1609 (2014).
- 1610 148. Imai, E. et al. Kidney disease screening program in Japan: history, outcome, and perspectives.  
1611 *Clin J Am Soc Nephrol* **2**, 1360-6 (2007).
- 1612 149. Khwaja, A. & Throssell, D. A critique of the UK NICE guidance for the detection and  
1613 management of individuals with chronic kidney disease. *Nephron Clin Pract* **113**, c207-13  
1614 (2009).
- 1615 150. Smith, J.M., Mott, S.A., Hoy, W.E. & International Federation of Kidney, F. Status of chronic  
1616 kidney disease prevention programs: International Federation of Kidney Foundation  
1617 Members 2005/2007. *Kidney Int* **74**, 1516-25 (2008).
- 1618 151. Tonelli, M. et al. How to advocate for the inclusion of chronic kidney disease in a national  
1619 noncommunicable chronic disease program. *Kidney Int* **85**, 1269-74 (2014).
- 1620 152. Hoerger, T.J. et al. A health policy model of CKD: 2. The cost-effectiveness of  
1621 microalbuminuria screening. *Am J Kidney Dis* **55**, 463-73 (2010).
- 1622 153. Perkovic, V. et al. Management of patients with diabetes and CKD: conclusions from a  
1623 "Kidney Disease: Improving Global Outcomes" (KDIGO) Controversies Conference. *Kidney Int*  
1624 **90**, 1175-1183 (2016).
- 1625 154. Ozyilmaz, A. et al. Screening for albuminuria with subsequent screening for hypertension and  
1626 hypercholesterolaemia identifies subjects in whom treatment is warranted to prevent  
1627 cardiovascular events. *Nephrol Dial Transplant* **28**, 2805-15 (2013).
- 1628 155. Tanaka, F. et al. Low-grade albuminuria and incidence of cardiovascular disease and all-cause  
1629 mortality in nondiabetic and normotensive individuals. *J Hypertens* **34**, 506-12; discussion  
1630 512 (2016).
- 1631 156. Shardlow, A., McIntyre, N.J., Fluck, R.J., McIntyre, C.W. & Taal, M.W. Chronic Kidney Disease  
1632 in Primary Care: Outcomes after Five Years in a Prospective Cohort Study. *PLoS Med* **13**,  
1633 e1002128 (2016).
- 1634 157. Grams, M.E. et al. Race, APOL1 Risk, and eGFR Decline in the General Population. *J Am Soc  
1635 Nephrol* **27**, 2842-50 (2016).
- 1636 158. Kovesdy, C.P., Furth, S.L., Zoccali, C. & World Kidney Day Steering, C. Obesity and Kidney  
1637 Disease: Hidden Consequences of the Epidemic. *Can J Kidney Health Dis* **4**,  
1638 2054358117698669 (2017).

- 1639 159. de Galan, B.E. et al. Lowering blood pressure reduces renal events in type 2 diabetes. *J Am  
1640 Soc Nephrol* **20**, 883-92 (2009).
- 1641 160. Oellgaard, J. et al. Intensified multifactorial intervention in type 2 diabetics with  
1642 microalbuminuria leads to long-term renal benefits. *Kidney Int* **91**, 982-988 (2017).
- 1643 161. Perkovic, V. et al. Intensive glucose control improves kidney outcomes in patients with type 2  
1644 diabetes. *Kidney Int* **83**, 517-23 (2013).
- 1645 162. Gross, O. et al. Early angiotensin-converting enzyme inhibition in Alport syndrome delays  
1646 renal failure and improves life expectancy. *Kidney Int* **81**, 494-501 (2012).
- 1647 163. Schievink, B. et al. Early renin-angiotensin system intervention is more beneficial than late  
1648 intervention in delaying end-stage renal disease in patients with type 2 diabetes. *Diabetes  
1649 Obes Metab* **18**, 64-71 (2016).
- 1650 164. Oliveira, B., Kleta, R., Bockenhauer, D. & Walsh, S.B. Genetic, pathophysiological, and clinical  
1651 aspects of nephrocalcinosis. *Am J Physiol Renal Physiol* **311**, F1243-F1252 (2016).
- 1652 165. Trautmann, A. et al. Spectrum of steroid-resistant and congenital nephrotic syndrome in  
1653 children: the PodoNet registry cohort. *Clin J Am Soc Nephrol* **10**, 592-600 (2015).
- 1654 166. Noris, M. & Remuzzi, G. Glomerular Diseases Dependent on Complement Activation,  
1655 Including Atypical Hemolytic Uremic Syndrome, Membranoproliferative Glomerulonephritis,  
1656 and C3 Glomerulopathy: Core Curriculum 2015. *Am J Kidney Dis* **66**, 359-75 (2015).
- 1657 167. Hildebrand, A.M., Huang, S.H. & Clark, W.F. Plasma exchange for kidney disease: what is the  
1658 best evidence? *Adv Chronic Kidney Dis* **21**, 217-27 (2014).
- 1659 168. Rauen, T. et al. Intensive Supportive Care plus Immunosuppression in IgA Nephropathy. *N  
1660 Engl J Med* **373**, 2225-36 (2015).
- 1661 169. Staplin, N. et al. Smoking and Adverse Outcomes in Patients With CKD: The Study of Heart  
1662 and Renal Protection (SHARP). *Am J Kidney Dis* **68**, 371-80 (2016).
- 1663 170. Cravedi, P., Ruggenenti, P. & Remuzzi, G. Intensified inhibition of renin-angiotensin system: a  
1664 way to improve renal protection? *Curr Hypertens Rep* **9**, 430-6 (2007).
- 1665 171. Schrier, R.W. et al. Blood pressure in early autosomal dominant polycystic kidney disease. *N  
1666 Engl J Med* **371**, 2255-66 (2014).
- 1667 172. Weir, M.R. et al. Effectiveness of patiromer in the treatment of hyperkalemia in chronic  
1668 kidney disease patients with hypertension on diuretics. *J Hypertens* **35 Suppl 1**, S57-S63  
1669 (2017).
- 1670 173. Holtkamp, F.A. et al. An acute fall in estimated glomerular filtration rate during treatment  
1671 with losartan predicts a slower decrease in long-term renal function. *Kidney Int* **80**, 282-7  
1672 (2011).
- 1673 174. Ruggenenti, P. et al. Role of remission clinics in the longitudinal treatment of CKD. *J Am Soc  
1674 Nephrol* **19**, 1213-24 (2008).
- 1675 175. Daina, E. et al. A multidrug, antiproteinuric approach to alport syndrome: a ten-year cohort  
1676 study. *Nephron* **130**, 13-20 (2015).
- 1677 176. Li, K. et al. Effects of Bariatric Surgery on Renal Function in Obese Patients: A Systematic  
1678 Review and Meta Analysis. *PLoS One* **11**, e0163907 (2016).
- 1679 177. Guideline development, g. Clinical Practice Guideline on management of patients with  
1680 diabetes and chronic kidney disease stage 3b or higher (eGFR <45 mL/min). *Nephrol Dial  
1681 Transplant* **30 Suppl 2**, ii1-142 (2015).
- 1682 178. Neal, B. et al. Canagliflozin and Cardiovascular and Renal Events in Type 2 Diabetes. *N Engl J  
1683 Med* (2017).
- 1684 179. Zinman, B. et al. Empagliflozin, Cardiovascular Outcomes, and Mortality in Type 2 Diabetes. *N  
1685 Engl J Med* **373**, 2117-28 (2015).
- 1686 180. Wanner, C., Amann, K. & Shoji, T. The heart and vascular system in dialysis. *Lancet* **388**, 276-  
1687 84 (2016).
- 1688 181. Rossignol, P. et al. Cardiovascular outcome trials in patients with chronic kidney disease:  
1689 challenges associated with selection of patients and endpoints. *Eur Heart J* (2017).

- 1690 182. Xu, X. et al. Efficacy of Folic Acid Therapy on the Progression of Chronic Kidney Disease: The  
1691 Renal Substudy of the China Stroke Primary Prevention Trial. *JAMA Intern Med* **176**, 1443-  
1692 1450 (2016).
- 1693 183. Baigent, C. et al. The effects of lowering LDL cholesterol with simvastatin plus ezetimibe in  
1694 patients with chronic kidney disease (Study of Heart and Renal Protection): a randomised  
1695 placebo-controlled trial. *Lancet* **377**, 2181-92 (2011).
- 1696 184. Cholesterol Treatment Trialists, C. et al. Impact of renal function on the effects of LDL  
1697 cholesterol lowering with statin-based regimens: a meta-analysis of individual participant  
1698 data from 28 randomised trials. *Lancet Diabetes Endocrinol* **4**, 829-39 (2016).
- 1699 185. Fellstrom, B.C. et al. Rosuvastatin and cardiovascular events in patients undergoing  
1700 hemodialysis. *N Engl J Med* **360**, 1395-407 (2009).
- 1701 186. Wanner, C. et al. Atorvastatin in patients with type 2 diabetes mellitus undergoing  
1702 hemodialysis. *N Engl J Med* **353**, 238-48 (2005).
- 1703 187. Kidney Disease: Improving Global Outcomes (KDIGO) Anemia Work Group. KDIGO Clinical  
1704 Practice Guideline for Anemia in Chronic Kidney Disease. . *Kidney Inter., Suppl.* **2**, 279-335  
1705 (2012).
- 1706 188. Kidney Disease: Improving Global Outcomes (KDIGO) Blood Pressure Work Group. KDIGO  
1707 Clinical Practice Guideline for the Management of Blood Pressure in Chronic Kidney Disease..  
1708 *Kidney inter., Suppl.* **2**, 337-414 (2012).
- 1709 189. KDIGO 2017 Clinical Practice Guideline Update for the Diagnosis, Evaluation, Prevention, and  
1710 Treatment of Chronic Kidney Disease–Mineral and Bone Disorder (CKD-MBD) *Kidney Int*  
1711 *Suppl* **7**, 1-59 (2017).
- 1712 190. Sumida, K. & Kovacs, C.P. Disease Trajectories Before ESRD: Implications for Clinical  
1713 Management. *Semin Nephrol* **37**, 132-143 (2017).
- 1714 191. Ricardo, A.C. et al. Influence of Nephrologist Care on Management and Outcomes in Adults  
1715 with Chronic Kidney Disease. *J Gen Intern Med* **31**, 22-9 (2016).
- 1716 192. Kolff, W.J. The artificial kidney. *J Mt Sinai Hosp N Y* **14**, 71-9 (1947).
- 1717 193. Tordoir, J. et al. EBPG on Vascular Access. *Nephrol Dial Transplant* **22 Suppl 2**, ii88-117  
1718 (2007).
- 1719 194. Ravani, P. et al. Associations between hemodialysis access type and clinical outcomes: a  
1720 systematic review. *J Am Soc Nephrol* **24**, 465-73 (2013).
- 1721 195. Xue, H. et al. Hemodialysis access usage patterns in the incident dialysis year and associated  
1722 catheter-related complications. *Am J Kidney Dis* **61**, 123-30 (2013).
- 1723 196. Alencar de Pinho, N. et al. Vascular access conversion and patient outcome after  
1724 hemodialysis initiation with a nonfunctional arteriovenous access: a prospective registry-  
1725 based study. *BMC Nephrol* **18**, 74 (2017).
- 1726 197. Wallace, E.L. et al. Catheter Insertion and Perioperative Practices Within the ISPD North  
1727 American Research Consortium. *Perit Dial Int* **36**, 382-6 (2016).
- 1728 198. Leurs, P., Machowska, A. & Lindholm, B. Timing of dialysis initiation: when to start? Which  
1729 treatment? *J Ren Nutr* **25**, 238-41 (2015).
- 1730 199. Abramowicz, D. et al. European Renal Best Practice Guideline on kidney donor and recipient  
1731 evaluation and perioperative care. *Nephrol Dial Transplant* **30**, 1790-7 (2015).
- 1732 200. Sebille, V. et al. Prospective, multicenter, controlled study of quality of life, psychological  
1733 adjustment process and medical outcomes of patients receiving a preemptive kidney  
1734 transplant compared to a similar population of recipients after a dialysis period of less than  
1735 three years--The PreKit-QoL study protocol. *BMC Nephrol* **17**, 11 (2016).
- 1736 201. Chang, P. et al. Living donor age and kidney allograft half-life: implications for living donor  
1737 paired exchange programs. *Clin J Am Soc Nephrol* **7**, 835-41 (2012).
- 1738 202. Allen, P.J. et al. Recurrent glomerulonephritis after kidney transplantation: risk factors and  
1739 allograft outcomes. *Kidney Int* (2017).

- 1740 203. Carson, R.C., Juszczak, M., Davenport, A. & Burns, A. Is maximum conservative management  
1741 an equivalent treatment option to dialysis for elderly patients with significant comorbid  
1742 disease? *Clin J Am Soc Nephrol* **4**, 1611-9 (2009).
- 1743 204. Morton, R.L. et al. Conservative Management and End-of-Life Care in an Australian Cohort  
1744 with ESRD. *Clin J Am Soc Nephrol* **11**, 2195-2203 (2016).
- 1745 205. Verberne, W.R. et al. Comparative Survival among Older Adults with Advanced Kidney  
1746 Disease Managed Conservatively Versus with Dialysis. *Clin J Am Soc Nephrol* **11**, 633-40  
1747 (2016).
- 1748 206. Crail, S., Walker, R., Brown, M. & Renal Supportive Care working, g. Renal supportive and  
1749 palliative care: position statement. *Nephrology (Carlton)* **18**, 393-400 (2013).
- 1750 207. Birmele, B. et al. Death after withdrawal from dialysis: the most common cause of death in a  
1751 French dialysis population. *Nephrol Dial Transplant* **19**, 686-91 (2004).
- 1752 208. Cox, K.J., Parshall, M.B., Hernandez, S.H., Parvez, S.Z. & Unruh, M.L. Symptoms among  
1753 patients receiving in-center hemodialysis: A qualitative study. *Hemodial Int* (2016).
- 1754 209. Jesky, M.D. et al. Health-Related Quality of Life Impacts Mortality but Not Progression to  
1755 End-Stage Renal Disease in Pre-Dialysis Chronic Kidney Disease: A Prospective Observational  
1756 Study. *PLoS One* **11**, e0165675 (2016).
- 1757 210. Rebollo Rubio, A., Morales Asencio, J.M. & Eugenia Pons Raventos, M. Depression, anxiety  
1758 and health-related quality of life amongst patients who are starting dialysis treatment. *J Ren  
1759 Care* (2017).
- 1760 211. Davison, S.N., Jhangri, G.S. & Johnson, J.A. Cross-sectional validity of a modified Edmonton  
1761 symptom assessment system in dialysis patients: a simple assessment of symptom burden.  
1762 *Kidney Int* **69**, 1621-5 (2006).
- 1763 212. Davison, S.N. Pain in hemodialysis patients: prevalence, cause, severity, and management.  
1764 *Am J Kidney Dis* **42**, 1239-47 (2003).
- 1765 213. Pereira, B.D.S. et al. Beyond quality of life: a cross sectional study on the mental health of  
1766 patients with chronic kidney disease undergoing dialysis and their caregivers. *Health Qual  
1767 Life Outcomes* **15**, 74 (2017).
- 1768 214. Tonelli, M. The roads less traveled? Diverging research and clinical priorities for dialysis  
1769 patients and those with less severe CKD. *Am J Kidney Dis* **63**, 124-32 (2014).
- 1770 215. Tinetti, M.E., Fried, T.R. & Boyd, C.M. Designing health care for the most common chronic  
1771 condition--multimorbidity. *JAMA* **307**, 2493-4 (2012).
- 1772 216. Cabrera, V.J., Hansson, J., Kliger, A.S. & Finkelstein, F.O. Symptom Management of the  
1773 Patient with CKD: The Role of Dialysis. *Clin J Am Soc Nephrol* **12**, 687-693 (2017).
- 1774 217. Manfredini, F. et al. Exercise in Patients on Dialysis: A Multicenter, Randomized Clinical Trial.  
1775 *J Am Soc Nephrol* **28**, 1259-1268 (2017).
- 1776 218. Cameron, J.I., Whiteside, C., Katz, J. & Devins, G.M. Differences in quality of life across renal  
1777 replacement therapies: a meta-analytic comparison. *Am J Kidney Dis* **35**, 629-37 (2000).
- 1778 219. Iyasere, O.U. et al. Quality of Life and Physical Function in Older Patients on Dialysis: A  
1779 Comparison of Assisted Peritoneal Dialysis with Hemodialysis. *Clin J Am Soc Nephrol* **11**, 423-  
1780 30 (2016).
- 1781 220. Vanholder, R. et al. Reducing the costs of chronic kidney disease while delivering quality  
1782 health care: a call to action. *Nat Rev Nephrol* **13**, 393-409 (2017).
- 1783 221. Dew, M.A. et al. Does transplantation produce quality of life benefits? A quantitative analysis  
1784 of the literature. *Transplantation* **64**, 1261-73 (1997).
- 1785 222. Rhee, C.M., Brunelli, S.M., Subramanian, L. & Tentori, F. Measuring patient experience in  
1786 dialysis: a new paradigm of quality assessment. *J Nephrol* (2017).
- 1787 223. Levin, A., Lancashire, W. & Fassett, R.G. Targets, trends, excesses, and deficiencies:  
1788 refocusing clinical investigation to improve patient outcomes. *Kidney Int* **83**, 1001-9 (2013).
- 1789 224. Wuttke, M. & Kottgen, A. Insights into kidney diseases from genome-wide association  
1790 studies. *Nat Rev Nephrol* **12**, 549-62 (2016).

- 1791 225. Beeman, S.C. et al. MRI-based glomerular morphology and pathology in whole human  
1792 kidneys. *Am J Physiol Renal Physiol* **306**, F1381-90 (2014).
- 1793 226. Boor, P., Ostendorf, T. & Floege, J. Renal fibrosis: novel insights into mechanisms and  
1794 therapeutic targets. *Nat Rev Nephrol* **6**, 643-56 (2010).
- 1795 227. Tampe, D. & Zeisberg, M. Potential approaches to reverse or repair renal fibrosis. *Nat Rev  
1796 Nephrol* **10**, 226-37 (2014).
- 1797 228. Voelker, J. et al. Anti-TGF-beta1 Antibody Therapy in Patients with Diabetic Nephropathy. *J  
1798 Am Soc Nephrol* **28**, 953-962 (2017).
- 1799 229. Goicoechea, M. et al. Allopurinol and progression of CKD and cardiovascular events: long-  
1800 term follow-up of a randomized clinical trial. *Am J Kidney Dis* **65**, 543-9 (2015).
- 1801 230. de Zeeuw, D. et al. Bardoxolone methyl in type 2 diabetes and stage 4 chronic kidney  
1802 disease. *N Engl J Med* **369**, 2492-503 (2013).
- 1803 231. Pergola, P.E. et al. Bardoxolone methyl and kidney function in CKD with type 2 diabetes. *N  
1804 Engl J Med* **365**, 327-36 (2011).
- 1805 232. Lazzeri, E., Romagnani, P. & Lasagni, L. Stem cell therapy for kidney disease. *Expert Opin Biol  
1806 Ther* **15**, 1455-68 (2015).
- 1807 233. Lasagni, L. et al. Podocyte Regeneration Driven by Renal Progenitors Determines Glomerular  
1808 Disease Remission and Can Be Pharmacologically Enhanced. *Stem Cell Reports* **5**, 248-63  
1809 (2015).
- 1810 234. Mazzinghi, B., Romagnani, P. & Lazzeri, E. Biologic modulation in renal regeneration. *Expert  
1811 Opin Biol Ther* **16**, 1403-1415 (2016).
- 1812 235. Pichaiwong, W. et al. Reversibility of structural and functional damage in a model of  
1813 advanced diabetic nephropathy. *J Am Soc Nephrol* **24**, 1088-102 (2013).
- 1814 236. Cianciolo Cosentino, C. et al. Histone deacetylase inhibitor enhances recovery after AKI. *J Am  
1815 Soc Nephrol* **24**, 943-53 (2013).
- 1816 237. Klinkhammer, B.M., Goldschmeding, R., Floege, J. & Boor, P. Treatment of Renal Fibrosis-  
1817 Turning Challenges into Opportunities. *Adv Chronic Kidney Dis* **24**, 117-129 (2017).
- 1818 238. Kramann, R. et al. Pharmacological GLI2 inhibition prevents myofibroblast cell-cycle  
1819 progression and reduces kidney fibrosis. *J Clin Invest* **125**, 2935-51 (2015).
- 1820 239. Peired, A.J., Sisti, A. & Romagnani, P. Mesenchymal Stem Cell-Based Therapy for Kidney  
1821 Disease: A Review of Clinical Evidence. *Stem Cells Int* **2016**, 4798639 (2016).
- 1822 240. Ninichuk, V. et al. Multipotent mesenchymal stem cells reduce interstitial fibrosis but do not  
1823 delay progression of chronic kidney disease in collagen4A3-deficient mice. *Kidney Int* **70**, 121-  
1824 9 (2006).
- 1825 241. Xinaris, C. et al. Functional Human Podocytes Generated in Organoids from Amniotic Fluid  
1826 Stem Cells. *J Am Soc Nephrol* **27**, 1400-11 (2016).
- 1827 242. Takasato, M. et al. Kidney organoids from human iPS cells contain multiple lineages and  
1828 model human nephrogenesis. *Nature* **536**, 238 (2016).
- 1829 243. Takasato, M. & Little, M.H. Making a Kidney Organoid Using the Directed Differentiation of  
1830 Human Pluripotent Stem Cells. *Methods Mol Biol* **1597**, 195-206 (2017).
- 1831 244. Xinaris, C., Brizi, V. & Remuzzi, G. Organoid Models and Applications in Biomedical Research.  
1832 *Nephron* **130**, 191-9 (2015).
- 1833 245. Anders, H.J., Jayne, D.R. & Rovin, B.H. Hurdles to the introduction of new therapies for  
1834 immune-mediated kidney diseases. *Nat Rev Nephrol* **12**, 205-16 (2016).
- 1835 246. Holderied, A. & Anders, H.J. Animal models of kidney inflammation in translational medicine.  
1836 *Drug Discovery Today: Disease Models* **11**, 19-27 (2014).
- 1837 247. Jayne, D.R. et al. Randomized Trial of C5a Receptor Inhibitor Avacopan in ANCA-Associated  
1838 Vasculitis. *J Am Soc Nephrol* (2017).
- 1839 248. Ketteler, M. et al. Executive summary of the 2017 KDIGO Chronic Kidney Disease-Mineral and  
1840 Bone Disorder (CKD-MBD) Guideline Update: what's changed and why it matters. *Kidney Int*  
1841 **92**, 26-36 (2017).

- 1842 249. Kidney Disease: Improving Global Outcomes (KDIGO) Lipid Work Group. KDIGO Clinical Practice  
1843 Guideline for Lipid Management in Chronic Kidney Disease. *Kidney Inter., Suppl.* **3**, 259–305  
1844 (2013).
- 1845 250. Farrington, K. et al. Clinical Practice Guideline on management of older patients with chronic  
1846 kidney disease stage 3b or higher (eGFR<45 mL/min/1.73 m<sup>2</sup>): a summary document from the  
1847 European Renal Best Practice Group. *Nephrol Dial Transplant* **32**, 9-16 (2017).
- 1848 251. Klessens, C.Q. et al. An autopsy study suggests that diabetic nephropathy is underdiagnosed.  
1849 *Kidney Int* **90**, 149-56 (2016).

1850

1851

1852 **References to highlight**

1853 **Introduction:**

1854

1855 Kidney Disease: Improving Global Outcomes (KDIGO) CKD Work Group. KDIGO clinical practice guideline  
1856 for the evaluation and management of chronic kidney disease. *Kidney Int Suppl* **3**, 1-150 (2013).  
1857 **Latest classification of CKD now implementing also albuminuria in a 2D matrix for stratification of the**  
1858 **risk for CKD progression and complications.**

1859

1860

1861 **Epidemiology:**

1862 Bello, A.K. et al. Assessment of Global Kidney Health Care Status. *JAMA* **317**, 1864-1881 (2017).  
1863 **Latest overview about kidney health care in all regions of the world displaying wide variation of**  
1864 **access to nephrology specialists, quality of diagnostic workup, and preferences for kidney**  
1865 **replacement therapy.**

1866

1867 Benghanem Gharbi, M. et al. Chronic kidney disease, hypertension, diabetes, and obesity in the adult  
1868 population of Morocco: how to avoid "over"- and "under"-diagnosis of CKD. *Kidney Int* **89**, 1363-71  
1869 (2016).  
1870 **CKD population study performed in Morocco presenting percentiles for repeated eGFR. Such GFR**  
1871 **percentiles of the respective local population would be extremely useful for patient care.**

1872

1873

1874 **Pathophysiology**

1875

1876 Laouari, D. et al. TGF-alpha mediates genetic susceptibility to chronic kidney disease. *J Am Soc Nephrol*  
1877 **22**, 327-35 (2011).  
1878 **First description of the TGF-alpha/EGFR axis as a driver of compensatory growth of remnant**  
1879 **nephrons. Targeting this pathway can limit the adaptive response turning into a maladaptive**  
1880 **pathomechanism of CKD progression.**

1881

1882 Peired, A. et al. Proteinuria impairs podocyte regeneration by sequestering retinoic acid. *J Am Soc*  
1883 *Nephrol* **24**, 1756-68 (2013).  
1884 **Description of how proteinuria suppresses podocyte regeneration from local podocyte precursors**  
1885 **inside the glomerulus.**

1886

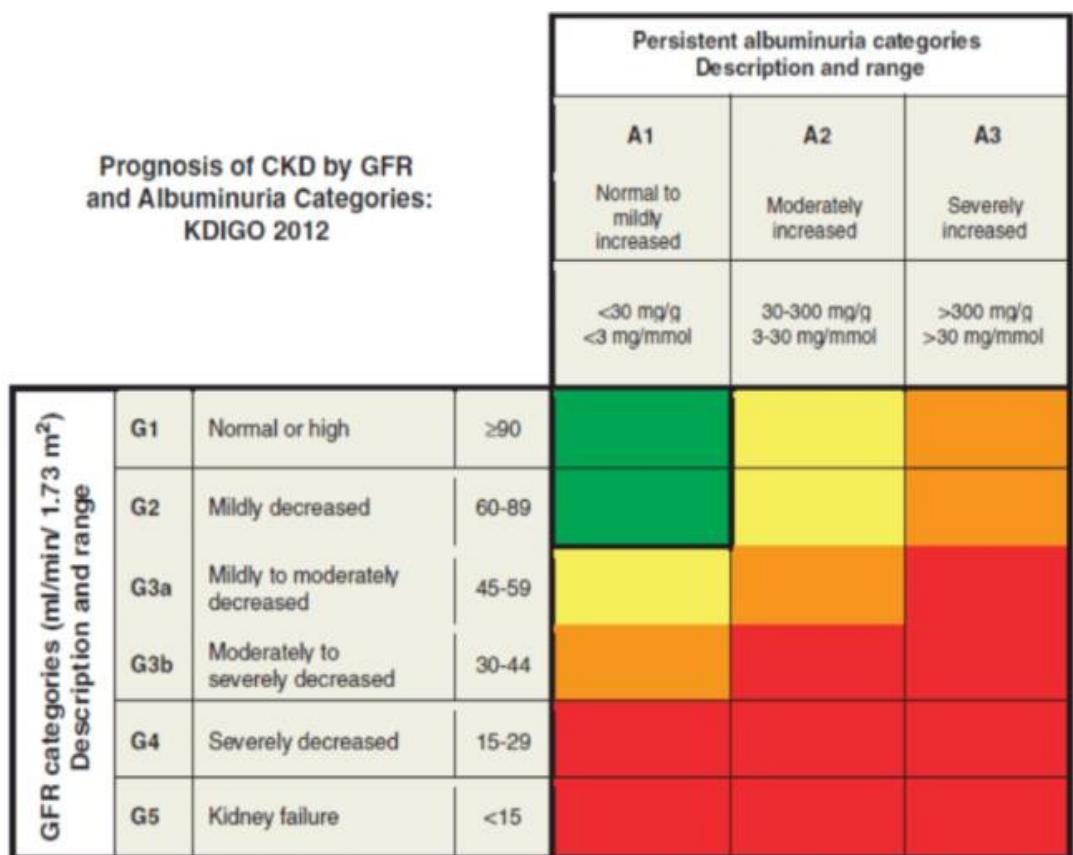
1887 Beckerman, P. et al. Transgenic expression of human APOL1 risk variants in podocytes induces kidney  
1888 disease in mice. *Nat Med* **23**, 429-438 (2017)

1889

- 1890 **Mechanistic mouse studies how APOL1 risk variants destabilize stressed podocytes and promote**  
1891 **CKD progression.**
- 1892
- 1893 Vallon, V. The mechanisms and therapeutic potential of SGLT2 inhibitors in diabetes mellitus. *Annu Rev Med* **66**, 255-70 (2015)
- 1894 **Comprehensive overview on the mechanism of action of SGLT2 inhibitors in diabetic kidney**
- 1895 **disease.**
- 1896
- 1897
- 1898
- 1899 **Diagnosis, screening, and prevention**
- 1900
- 1901 Chronic Kidney Disease Prognosis, C. et al. Association of estimated glomerular filtration rate and  
1902 albuminuria with all-cause and cardiovascular mortality in general population cohorts: a collaborative  
1903 meta-analysis. *Lancet* **375**, 2073-81 (2010).
- 1904 **Meta-analysis providing the rationale for all-cause mortality risk prediction using eGFR and**  
1905 **albuminuria levels as implemented in the KDIGO CKD stages.**
- 1906 **for all-cause mortality**
- 1907
- 1908 Fink, H.A. et al. Screening for, monitoring, and treatment of chronic kidney disease stages 1 to 3: a  
1909 systematic review for the U.S. Preventive Services Task Force and for an American College of  
1910 Physicians Clinical Practice Guideline. *Ann Intern Med* **156**, 570-81 (2012).
- 1911 **A critical discussion of the benefits and risks of CKD screening**
- 1912
- 1913 Lazarus, B. et al. Proton Pump Inhibitor Use and the Risk of Chronic Kidney Disease. *JAMA Intern Med*  
1914 **176**, 238-46 (2016).
- 1915 **Study raising concerns about a causal link between the common use of proton pump inhibitors and**  
1916 **CKD.**
- 1917
- 1918
- 1919
- 1920 **Management**
- 1921
- 1922 Wanner, C. et al. Empagliflozin and Progression of Kidney Disease in Type 2 Diabetes. *N Engl J Med*  
1923 **375**, 323-34 (2016).
- 1924 **First study to prove profound nephroprotective effects of an SGLT2 inhibitor in patients with CKD**  
1925 **and diabetes**
- 1926
- 1927 Rauen, T. et al. Intensive Supportive Care plus Immunosuppression in IgA Nephropathy. *N Engl J Med*  
1928 **373**, 2225-36 (2015)
- 1929 **If well done conservative treatment is very potent in preventing CKD progression in IgA**  
1930 **nephropathy**
- 1931
- 1932 Ruggenenti, P. et al. Role of remission clinics in the longitudinal treatment of CKD. *J Am Soc Nephrol*  
1933 **19**, 1213-24 (2008). **If rigorously done conservative treatment can be very potent in preventing CKD**  
1934 **progression in many forms of kidney disease**
- 1935
- 1936
- 1937
- 1938 **Quality of life**
- 1939
- 1940 Rebollo Rubio, A., Morales Asencio, J.M. & Eugenia Pons Raventos, M. Depression, anxiety and  
1941 health-related quality of life amongst patients who are starting dialysis treatment. *J Ren Care* (2017)

- 1942 **Improving quality of life starts with its proper assessment.**
- 1943
- 1944 Iyasere, O.U. et al. Quality of Life and Physical Function in Older Patients on Dialysis: A Comparison of  
1945 Assisted Peritoneal Dialysis with Hemodialysis. *Clin J Am Soc Nephrol* **11**, 423-30 (2016).
- 1946 **Evaluating alternative options to hemodialysis for older ESKD patients.**
- 1947
- 1948
- 1949
- 1950 **Outlook**
- 1951
- 1952 Levin, A. et al. Global kidney health 2017 and beyond: a roadmap for closing gaps in care, research,  
1953 and policy. *Lancet* (2017).
- 1954 **Roadmap on how to close gaps in global kidney health**
- 1955
- 1956
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Figure 1



Green: low risk (if no other markers of kidney disease, no CKD); Yellow: moderately increased risk;  
Orange: high risk; Red, very high risk.

Figure 2

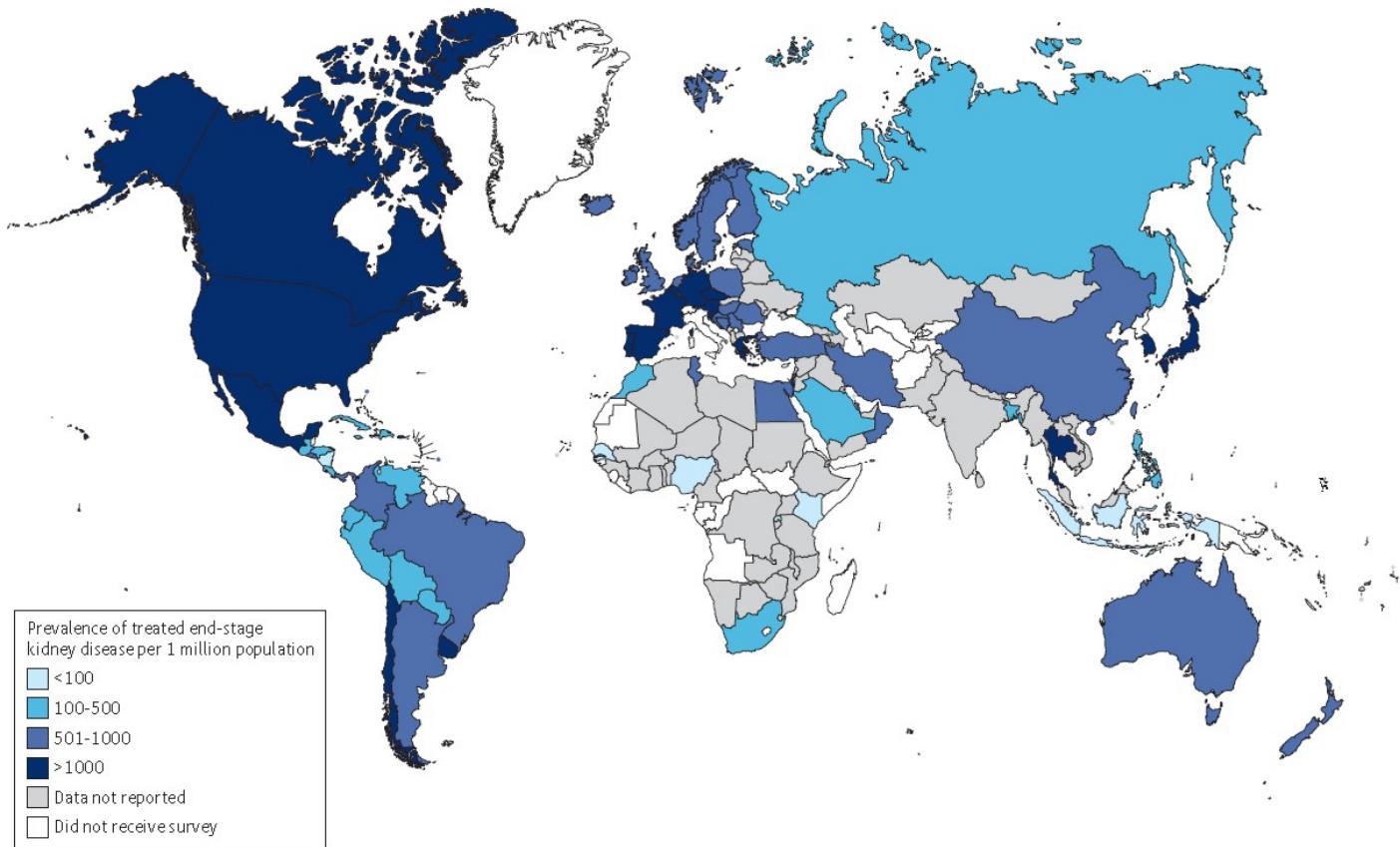
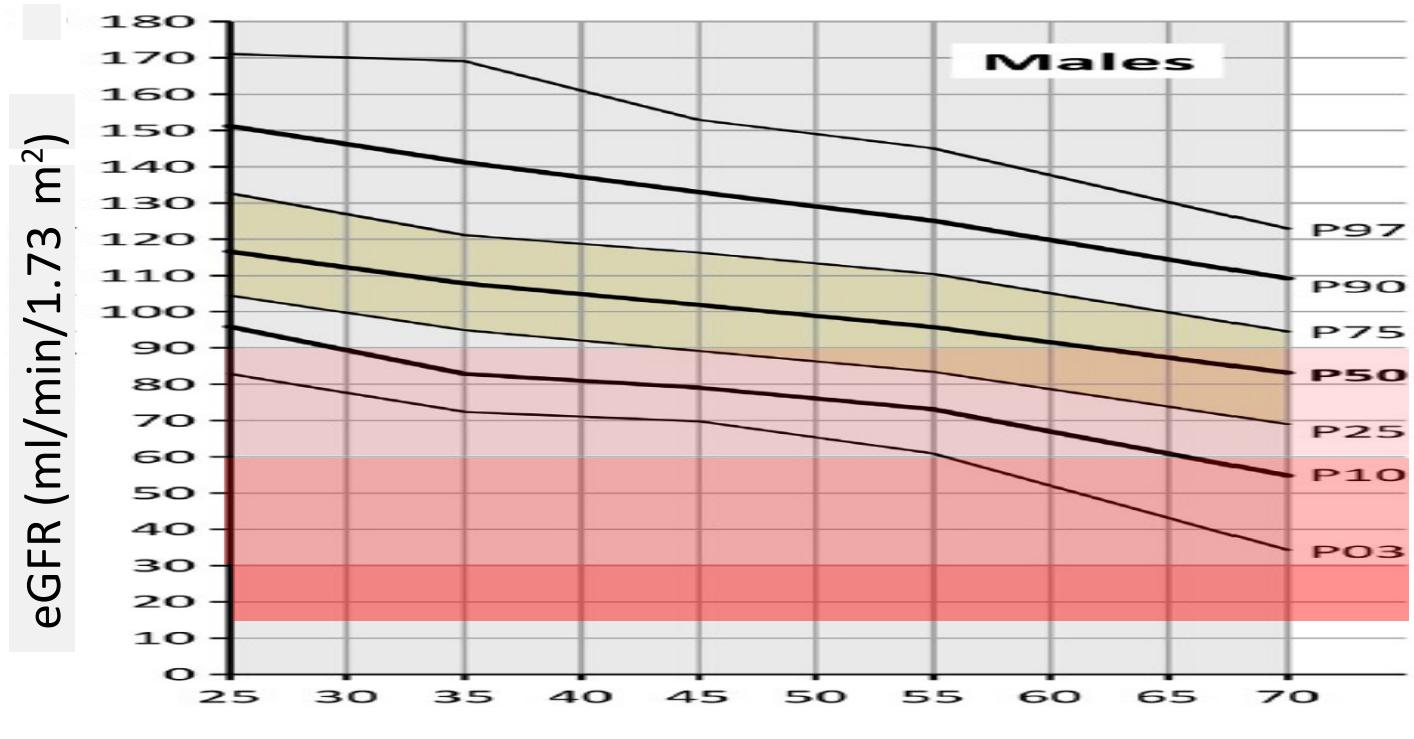


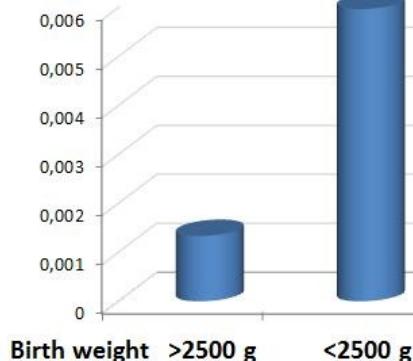
Figure 3



Age (years)



Risk for CKD in %



C

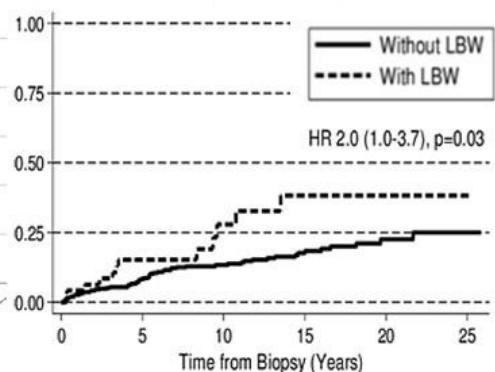


Figure 4

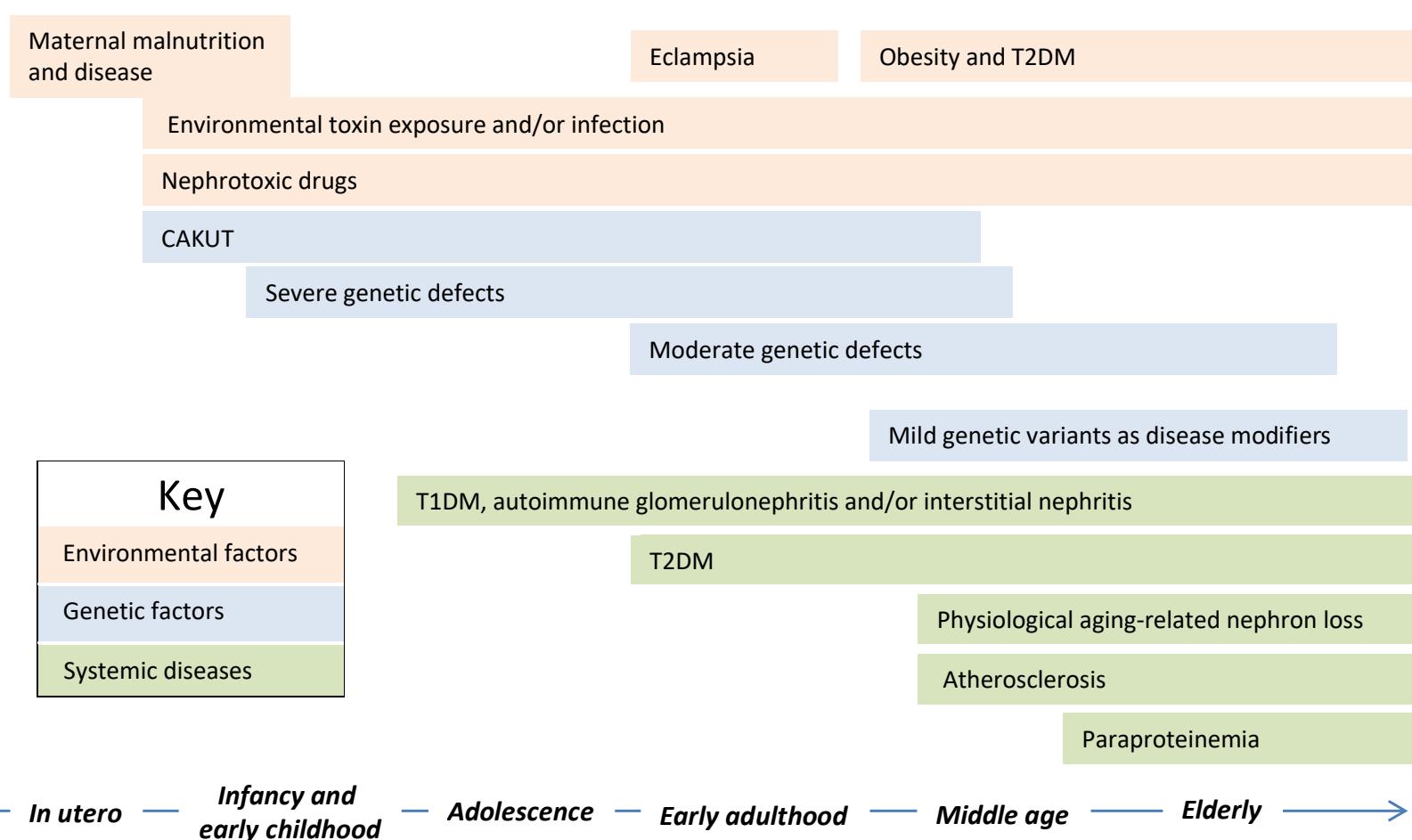
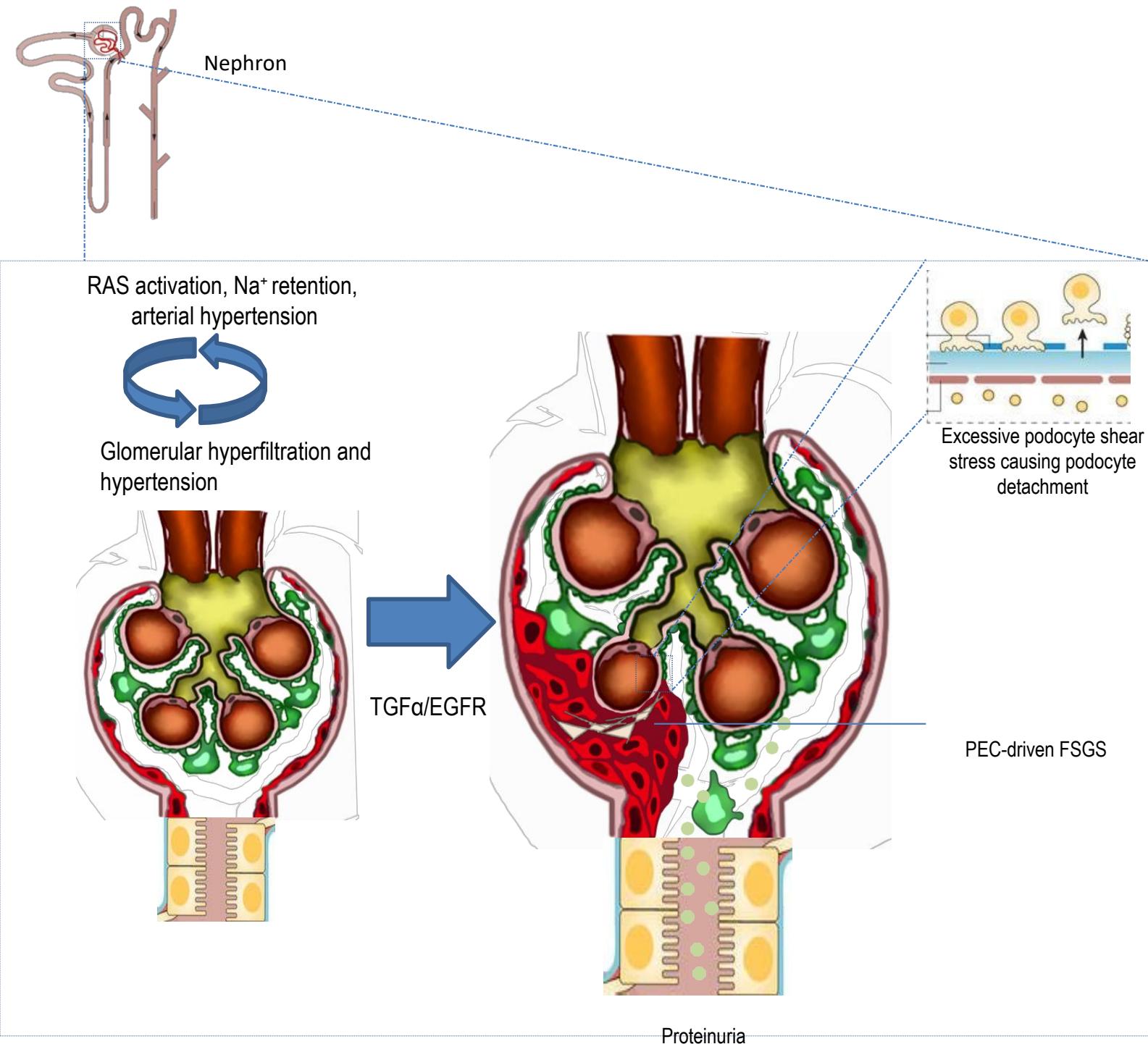


Figure 5A



podocyte



PEC



ECM



Detaching podocyte



Blood vessel



proteinuria

Figure 5B

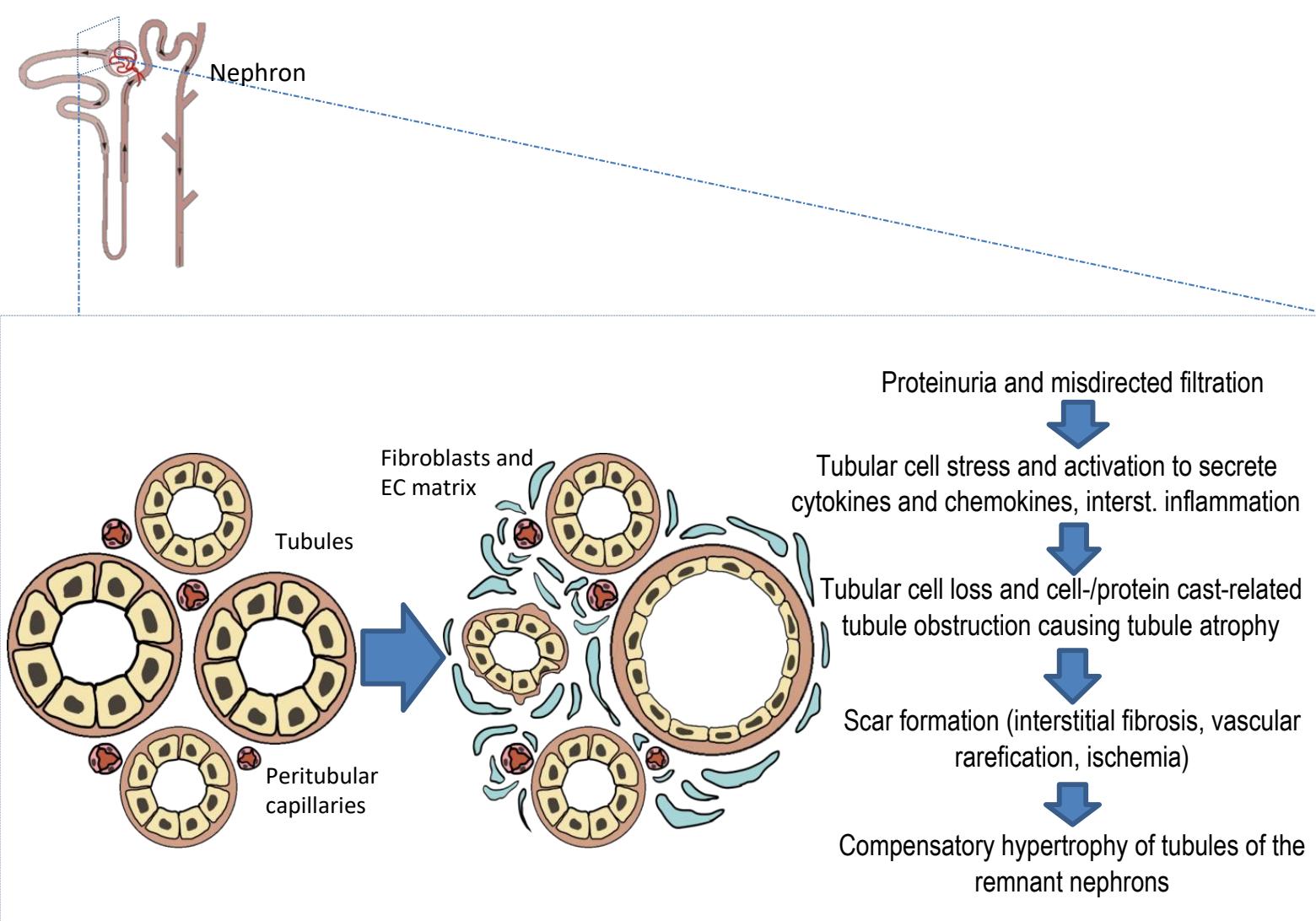
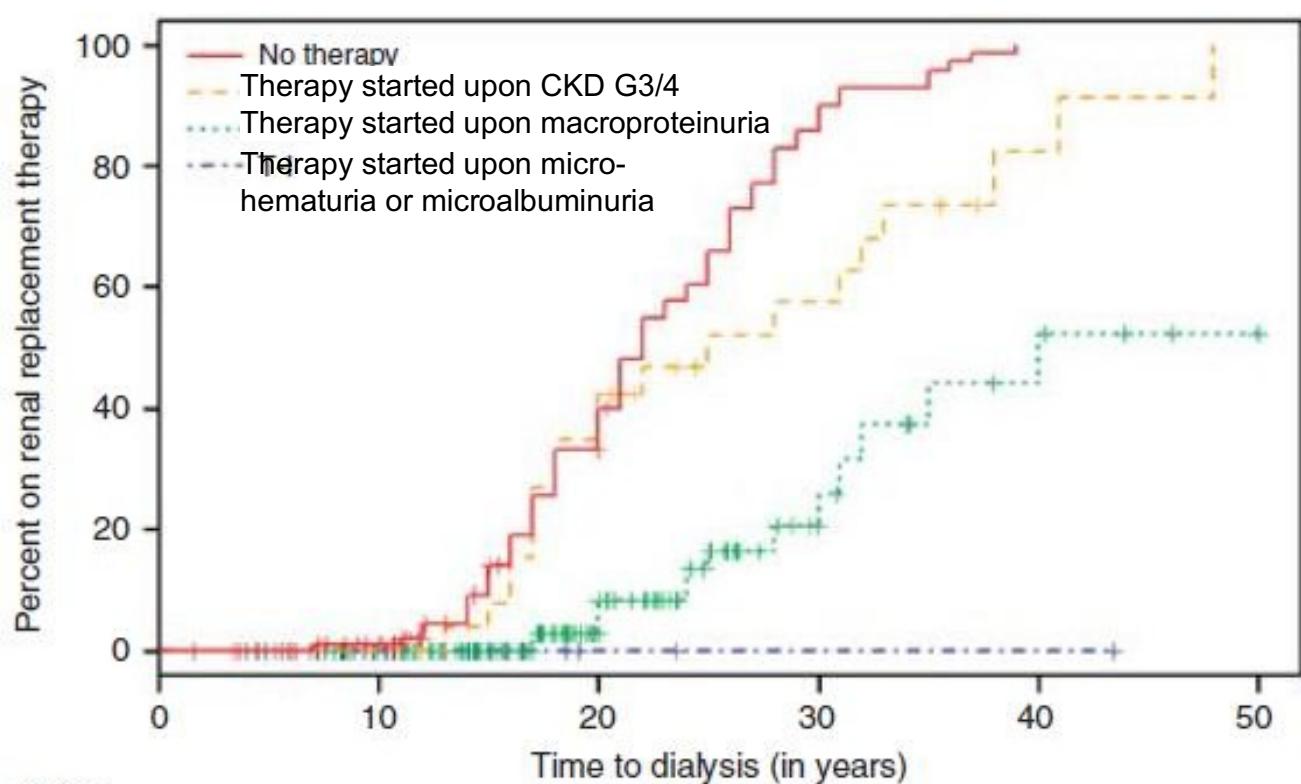


Figure 6



## No. at risk

	109	105	96	75	50	29	10	5	0	0	0
T-III	26	26	26	25	17	10	8	5	2	1	0
T-II	115	113	105	84	52	31	15	9	7	4	3
T-I	33	32	20	8	2	1	1	1	1	0	0

Figure 7

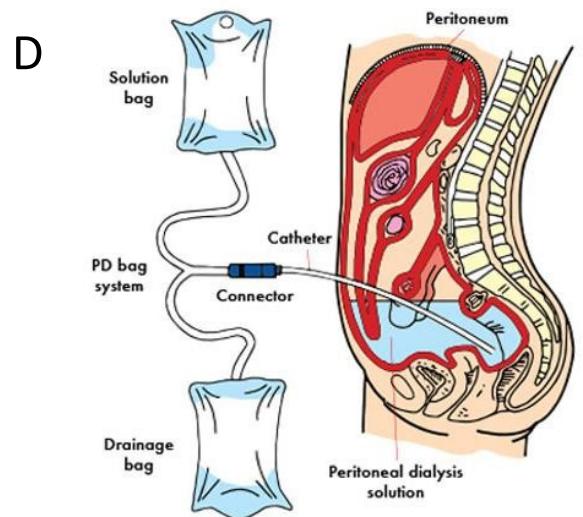
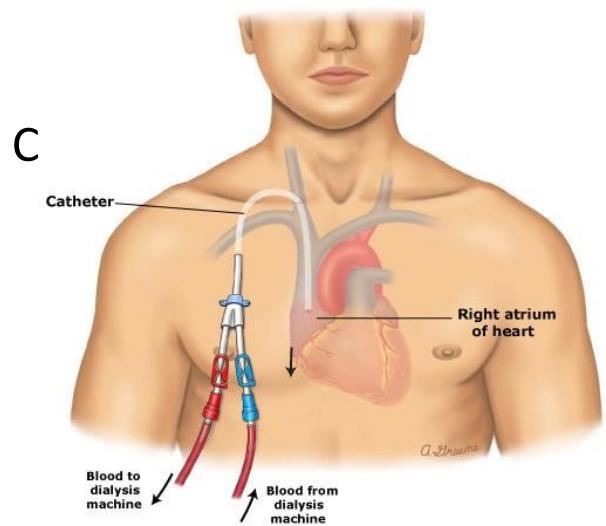
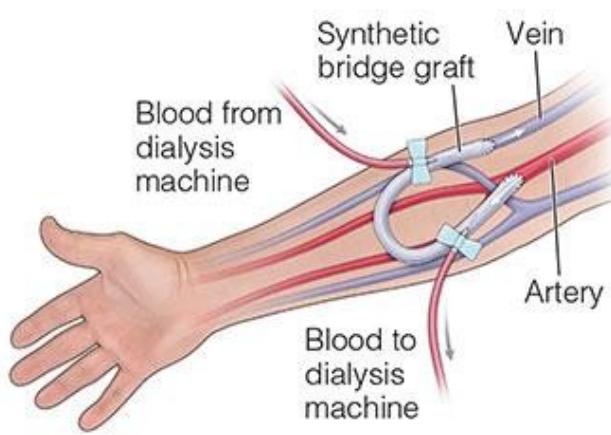
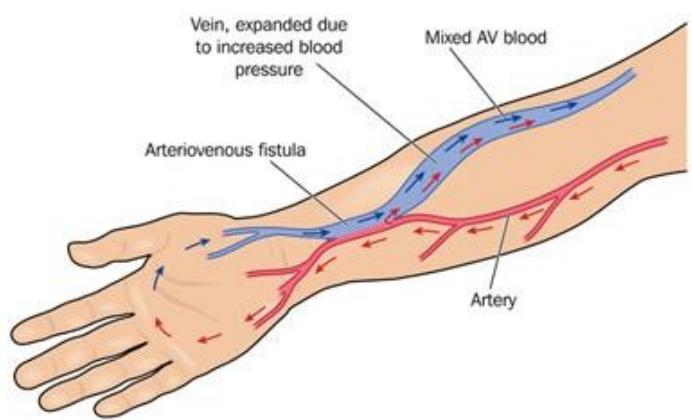
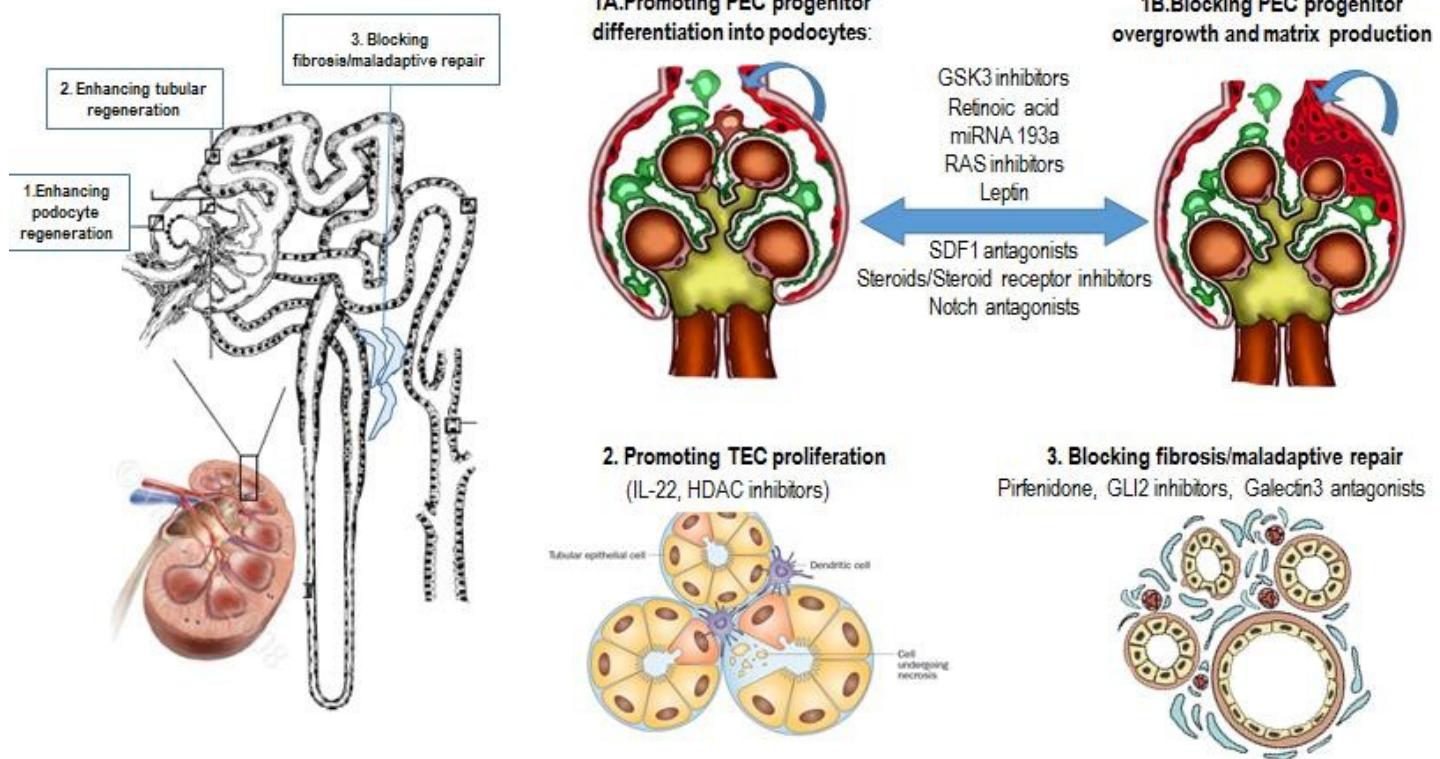
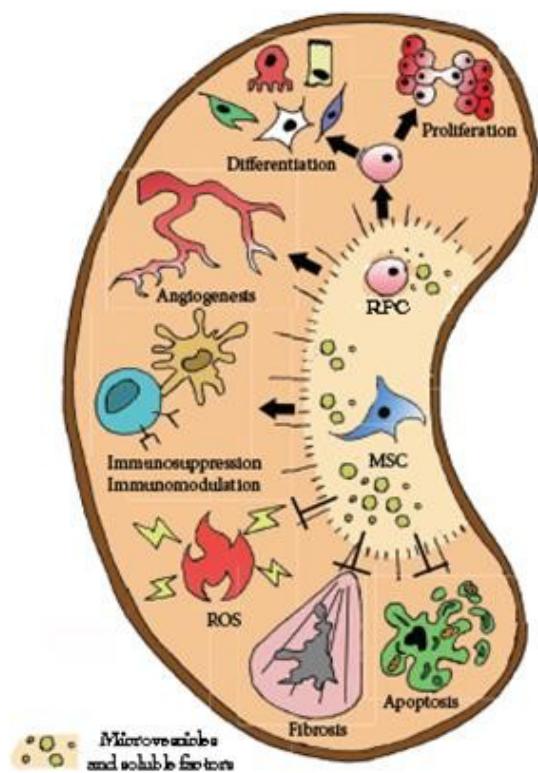


Figure 8



igure 9

A



B

