Exclusive CX3CR1 dependence of kidney DCs impacts glomerulonephritis progression


Introduction

DCs exist in virtually all organs. They gather antigens and activate T cells after migrating into the draining lymph nodes. Additionally, tissue-resident DCs modulate local immune responses by regulating infiltrating effector cells or memory T cells (1–4). Tissue macrophages (MPs) differ from DCs by a higher capacity to endocytose and degrade antigen and to clear pathogens and apoptotic cells and by a lower ability to activate T cells (5). The classification of APCs as DCs or MPs is still controversial. The demarcation between MP and DC functions is not absolute, and cells with combined functionality in varying degrees exist (5). We recently demonstrated that kidney cells expressing CD11c and MHC-II possessed DC, but not MP, functionality (6). A recent transcriptome analysis of CD11c+ kidney cells supported this classification (7).

In the healthy kidney, DCs form an extensive network in the tubulointerstitium (8) that maintains tissue homeostasis and serves sentinel functions against various forms of injury (9, 10). They play a sentinel role in pyelonephritis (PN), the most common renal infection, in which uropathogenic E. coli ascend from the bladder through the tubular system into the kidney (23). Little is known about the role of CX3CR1 in tissue DC function in the healthy and inflamed kidney cortex, and to a lesser degree in the kidney medulla and intestine, but not in other organs. CX3CR1 also promoted influx of DC precursors in crescentic glomerulonephritis, a DC-dependent aggressive type of nephritis. Disease severity was strongly attenuated in CX3CR1-deficient mice. Primarily CX3CR1-dependent DCs in the kidney cortex processed antigen for the intrarenal stimulation of T helper cells, a function important for glomerulonephritis progression. In contrast, medullary DCs played a specialized role in inducing innate immunity against bacterial pyelonephritis by recruiting neutrophils through rapid chemokine production. CX3CR1 deficiency had little effect on the immune defense against pyelonephritis, as medullary DCs were less CX3CR1 dependent than cortical DCs and because recruited neutrophils produced chemokines to compensate for the DC paucity. These findings demonstrate that cortical and medullary DCs play specialized roles in their respective kidney compartments. We identify CX3CR1 as a potential therapeutic target in glomerulonephritis that may involve fewer adverse side effects, such as impaired anti-infectious defense or compromised DC functions in other organs.

Conflict of interest: The authors have declared that no conflict of interest exists.

Citation for this article: J Clin Invest. 2013;123(10):4242–4254. doi:10.1172/JCI70143.
GN (25). Concomitantly, an infiltration of CX3CR1+ monocytes and T cells into inflamed kidneys was observed in patients (26, 27).

Preclinical studies in disease models showed both beneficial and adverse effects of CX3CR1 in a context-dependent manner. Thus, CX3CR1 aggravated heart transplant rejection (28) and arteriosclerosis by recruiting monocytes and promoting their survival (29, 30). Conversely, CX3CR1 also enhanced monocyte survival in liver injury, but this attenuated hepatitis (31). Other protective roles of CX3CR1 include preventing subretinal accumulation of microglia in degenerative macular eye disease (32) and monocyte recruitment to the spleen in listeriosis (33). In kidney ischemia/reperfusion and hypertensive kidney fibrosis, CX3CR1 contributed to monocyte recruitment (34) and aggravated fibrosis (35, 36). Conflicting studies exist on the role of CX3CR1 in GN. While antibody blockade of CX3CR1 reduced monocyte and CD8+ T cell infiltration and ameliorated disease in rats (37), immune complex GN in CD1 mice was unaltered in CX3CR1-deficient mice (28). The role of CX3CR1 in NTN is presently unclear.

The kidney can be macroscopically divided into 2 compartments, the cortex and the medulla, which harbor different parts of the nephrons. The glomeruli and the proximal tubuli are found in the cortex, and the descending loop of Henle enters the medulla, returns to the cortex, and continues as the distal tubule, which enters the collecting tubules that again descend into the medulla. DCs are located in both compartments, but due to differential blood supply and osmotic concentrations they encounter highly differential environmental conditions. There is no information about functional differences between cortical and medullary DCs. Here, we hypothesized that cortical DCs might be critical in GN, as the glomeruli are located in the cortex, whereas medullary DCs might be more important in PN, because the ascending bacteria first pass through the medulla. Our present findings confirm this hypothesis and demonstrate that CX3CR1 preferentially affects cortical DCs, identifying new therapeutic opportunities in GN.

**Results**

**Dependence of kidney DCs and MPs on CX3CR1 in healthy mice.**

CX3CR1 is abundantly expressed on most kidney APCs, whereas other immune cells constituted only minor fractions among
CX3CR1+ kidney cells (ref. 8 and Supplemental Figure 1, A–C; supplemental material available online with this article; doi:10.1172/JCI70143DS1). The functional role of CX3CR1 in kidney APCs is unclear. When we compared kidney sections of CX3CR1GFP/+ mice (expressing a GFP reporter in CX3CR1+ cells) and of CX3CR1GFP/GFP mice (expressing the GFP reporter and deficient for CX3CR1) by fluorescence microscopy, an obvious reduction of GFP+ cells in the absence of CX3CR1 was noted (Figure 1A). Analysis of kidney single cell suspensions by flow cytometry (gating strategy shown in Supplemental Figure 1D) revealed that exclusively the CX3CR1+ APCs expressing CD11c, which have been shown to possess DC functionality (6), were reduced by 75% in CX3CR1GFP/GFP mice, whereas CD11c– MPs were slightly, albeit not statistically significantly, enhanced (Figure 1B). Total DC and MP numbers did not differ between WT and CX3CR1GFP/+ mice (Supplemental Figure 2A), indicating that the latter could serve as CX3CR1-competent controls.

To study whether the reduction in DC numbers was unique to the kidney, we compared their abundance in different tissues from CX3CR1GFP/+ and CX3CR1GFP/GFP mice. There was no reduction in liver, lung, heart, bladder, lymph nodes, or spleen (Figure 1C). DCs were less frequent in CX3CR1-deficient mice in the small intestine, but their absolute numbers were more than an order of magnitude lower than in 1 kidney (Figure 1C). The spleens of CX3CR1GFP/GFP mice contained approximately 40% more GFP+ DCs than those of CX3CR1GFP/+ controls (Figure 1C), which might be explained by different homing of DC precursors.

CD11c+ GFP+ MPs were substantially reduced in the intestines of CX3CR1-deficient mice (Supplemental Figure 2B), consistent with a recent report (22). There was no reduction of CD11c+ GFP+ cells in kidney, liver, lung, heart, bladder, dermis, epidermis, bone marrow, spleen, and brain (Supplemental Figure 2C).

We speculated that the particularly strong CX3CR1 dependence of DCs in the kidney might be due to high expression of its ligand, CX3CL1, in this organ. Indeed, when we determined CX3CL1 by quantitative RT-PCR, its expression in the kidney was much higher than that in other organs except the small intestine (Figure 1D), providing a plausible explanation as to why DCs depended on CX3CR1 only in these organs (Figure 1C). There were no differences in CX3CL1 expression between CX3CR1-deficient and competent mice (Supplemental Figure 2D), ruling out feedback regulation of ligand expression by the receptor.

Dependence of kidney DCs and MPs on CX3CR1 in NTN. To study whether kidney DCs depended on CX3CR1 also under inflammatory conditions, we induced NTN, a widely studied model for crescentic GN. Ten days after disease induction, GFP+ DCs were scarcer in the kidneys of CX3CR1GFP/GFP mice compared with CX3CR1GFP/+ mice (Figure 2A). Of note, there was also a slight, albeit not statistically significant, reduction of renal GFP+ MP numbers at that time point (Figure 2A). Of note, there was also a slight, albeit not statistically significant, reduction of renal GFP+ MP numbers at that time point (Figure 2A). Of note, there was also a slight, albeit not statistically significant, reduction of renal GFP+ MP numbers at that time point (Figure 2A).
We next asked whether the reduction of kidney DCs in nephritic CX3CR1GFP/GFP mice was only a consequence of the reduced DC numbers under homeostatic conditions (Figure 1B) or whether the recruitment of DC precursors under inflammatory conditions also depended on CX3CR1. We addressed this question by adoptively transferring 10⁶ GFP⁺ bone marrow cells from CX3CR1GFP⁺/⁻ and CX3CR1GFP/GFP mice into WT mice 1 day after NTN induction. More than 60% of the GFP⁺ bone marrow cells expressed Ly6C, which is characteristic of inflammatory monocytes (Figure 2B). Influx of GFP⁺ cells into the kidneys was analyzed 2 and 4 days after transfer. GFP⁺ cells expressing the DC markers CD11c and MHC-II were detected in inflamed kidneys (Figure 2C). Importantly, far fewer CX3CR1-deficient cells entered nephritic kidneys at both time points (Figure 2D), whereas more of them were recovered from the spleens (Figure 2E). This indicates that CX3CR1 contributes to entry of DC precursors into the inflamed kidney. In the absence of CX3CR1, these cells relocated to the spleen, similar to our observations in healthy mice (Figure 1C). We did not detect the marker Ly6C on immigrated DCs (data not shown). This may be due to the rapid loss of this marker soon after tissue entry of Ly6C⁺ monocytes, as recently shown in the lung (38).

CX3CR1 deficiency attenuates NTN. We recently showed that kidney DC maturation stimulates the intrarenal DTH that drives NTN (13). The dearth of DCs in nephritic CX3CR1GFP/GFP mice was only a consequence of the reduced DC numbers under homeostatic conditions (Figure 1B) or whether the recruitment of DC precursors under inflammatory conditions also depended on CX3CR1. We addressed this question by adoptively transferring 10⁶ GFP⁺ bone marrow cells from CX3CR1GFP⁺/⁻ and CX3CR1GFP/GFP mice into WT mice 1 day after NTN induction. More than 60% of the GFP⁺ bone marrow cells expressed Ly6C, which is characteristic of inflammatory monocytes (Figure 2B). Influx of GFP⁺ cells into the kidneys was analyzed 2 and 4 days after transfer. GFP⁺ cells expressing the DC markers CD11c and MHC-II were detected in inflamed kidneys (Figure 2C). Importantly, far fewer CX3CR1-deficient cells entered nephritic kidneys at both time points (Figure 2D), whereas more of them were recovered from the spleens (Figure 2E). This indicates that CX3CR1 contributes to entry of DC precursors into the inflamed kidney. In the absence of CX3CR1, these cells relocated to the spleen, similar to our observations in healthy mice (Figure 1C). We did not detect the marker Ly6C on immigrated DCs (data not shown). This may be due to the rapid loss of this marker soon after tissue entry of Ly6C⁺ monocytes, as recently shown in the lung (38).

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Functionally, parameters like creatinine clearance, blood urea nitrogen, and proteinuria were improved in CX3CR1GFP/GFP mice (Figure 3, C–E), and histological examination of kidney sections revealed fewer tubular casts and crescents in CX3CR1GFP/GFP mice on day 10 (Supplemental Figure 3C), indicating that the loss of CX3CR1 attenuates NTN. On day 15, the histological features of kidney damage were even more pronounced (Figure 4, A–C). CX3CR1GFP/GFP mice also featured fewer periglomerular F4/80⁺ cells (Figure 4, D and E), indicating a reduction in DCs and/or MPs. Despite their reduced numbers (Figure 2A), kidney DCs of CX3CR1GFP/GFP mice still formed periglomerular infiltrates (6) in NTN (Figure 4F), indicating that CX3CR1 was dispensable for intrarenal APC migration toward inflamed glomeruli.

Cell-intrinsic DC functions are independent of CX3CR1 expression. To understand how CX3CR1 deficiency attenuated intrarenal DTH and nephritis symptoms, we asked whether DCs were functionally defective in the absence of this receptor. We first examined the systemic Th1 response against sheep Ig, which is induced by DCs in lymphatic tissues after injection of the nephrotoxic sheep serum (39). This response was unaltered, as evidenced by similar subcutaneous DTH response against sheep Ig (Figure 5A) and by similar production of the Th1 and Th17 cytokines, IFN-γ, TNF, and IL-17, by splenocytes (Figure 5B). These findings excluded the possibility that the attenuated intrarenal DTH response in CX3CR1GFP/GFP mice resulted from a failure to activate a nephritogenic T cell response. We therefore focused on intrarenal DCs. CX3CR1-deficient and -competent kidney DCs from nephritic mice expressed equal levels of costimulatory molecules and MHC-II (Figure 5C). Next, we studied their ability to capture antigen by injecting the model protein, OVA, a 45-kDa protein that can constitutively pass the glomerular filter (40). Regardless of CX3CR1 expression, DCs took up similar amounts of OVA (Figure 5D). To examine the principal DC function, the activation of naive T cells, we injected CX3CR1-deficient and CX3CR1-competent nephritic mice with OVA and cocultured kidney DCs with OVA-specific Th cells (OT-II cells). CX3CR1GFP⁺ and CX3CR1GFP/GFP DCs elicited similar
proliferation profiles and cytokine production by OT-II cells (Figure 5, E and F). Therefore, the observed differences in disease severity were not due to DC-intrinsic functional defects, supporting their reduced numbers as an underlying reason.

DCs in the renal cortex are especially dependent on CX3CR1. When we reexamined kidney sections of healthy CX3CR1+/+ and CX3CR1GFP/GFP mice by immunofluorescence microscopy, the paucity of GFP+ cells in the latter mice seemed to preferentially affect the kidney cortex (Figure 6A). To verify this histological impression in a quantitative manner and to distinguish between DCs and MPs, we surgically separated the renal medulla from the cortex, produced single cell suspensions by separate collagen digestion, and analyzed these by flow cytometry. The cortex of CX3CR1GFP/+ mice contained 3 times more GFP+ cells than the medulla, and 80% of them expressed the DC marker CD11c, whereas less than 40% of GFP+ cells in the medulla did so (Figure 6B and C). Consequently, the absolute numbers of GFP+ DCs were about 6 times higher in the cortex than in the medulla (Figure 6D). In CX3CR1GFP/GFP mice, DC numbers were reduced 9 fold from 200 × 10^3 to 22 × 10^3 cells per kidney cortex, whereas medulary DCs were reduced 3.5 fold from 38 × 10^3 to 11 × 10^3 cells per kidney (Figure 6D). MP numbers were increased 2.5 fold in the cortices of CX3CR1GFP/GFP mice (Figure 6E). Of note, the mice used in this experiment were younger than those used in the other experiments (Figure 1 and Figure 6, G and H), explaining the relatively low absolute DC numbers. Nevertheless, DC numbers were similarly reduced, indicating that the kidney DC deficiency in CX3CR1-deficient mice was age independent.

The kidney cortices of nephritic CX3CR1GFP/+ mice contained 416 × 10^3 GFP+ DCs, compared with 164 × 10^3 DCs in CX3CR1GFP/GFP mice (60% reduction), whereas only 96 × 10^3 DCs were seen in those of CX3CR1-deficient mice (55% reduction) (Figure 6F). Thus, even though proportional DC reduction was similar, the absolute deficit of kidney DCs in nephritis was more prominent in the cortex (–252 × 10^3 DCs) than in the medulla (–52 × 10^3 DCs). Furthermore, there were approximately 32 × 10^3 fewer MPs in the cortices and approximately 20 × 10^3 fewer medullary MPs in CX3CR1-deficient nephritic...
mice (Figure 6G). Taken together, our findings demonstrated that, under homeostatic conditions, CX3CR1 primarily affected DCs in the cortex, and, in the condition of nephritis, affected both cortical and medullary DCs and to a lesser extend also MPs.

Cortical, but not medullary, DCs can stimulate Th cells in GN. We reasoned that the proximity of cortical DCs to the glomeruli might render these cells particularly relevant in GN. When we compared the phenotype of medullary and cortical APCs in healthy mice, we observed similar expression of CD11b, F4/80, and CX3CR1 and higher CD11c expression on cortical CX3CR1+ cells (Figure 7A). For the most part, cortical and medullary DCs expressed similar levels of MHC-II and of the costimulatory molecules CD80, CD86, and CD40 under homeostatic conditions (Figure 7B), notwithstanding some variability of expression levels between experiments. In nephritic mice, expression of CD40 and MHC-II on cortical DCs slightly exceeded that on medullary DCs in 3 out of 5 experiments, consistent with higher maturation of the former (Figure 7B).

NTN is driven by a Th cell–dependent intrarenal DTH (11). Therefore, we cocultured cortical and medullary DCs with the model antigen, OVA, and OT-II cells. OVA-loaded cortical and medullary DCs from healthy mice caused little T cell proliferation compared with control splenic DCs (Figure 7C). By contrast, OVA-loaded DCs from the cortices of nephritic mice induced strong OT-II cell proliferation (Figure 7, C and D) and secretion of IFN-γ and IL-17 (Figure 7E). Remarkably, medullary DCs from nephritic kidneys still only elicited minimal OT-II cell proliferation and cytokine production (Figure 7, C–E). These results suggested that Th cell stimulation during NTN depends mainly on cortical DCs, implying that only these DCs drive NTN progression.
Medullary DCs poorly process antigen for MHC-II presentation. To understand why medullary DCs poorly stimulated Th cells, we first examined their survival in vitro. A similar fraction of cortical and medullary DCs survived a culture period of 24 hours (cortical DCs: 55.4% ± 0.7% survival; medullary DCs: 58.5% ± 2.4% survival), excluding selective death as underlying reason. DC maturation parameters differed little (Figure 7B). We therefore speculated about distinct antigen handling as an underlying reason and first asked whether medullary DCs were unable to endocytose antigen. However, medullary DCs captured slightly more fluorescent OVA than cortical DCs in an in vitro culture both under homeostatic conditions (Figure 8, A and B) and in NTN (Figure 8B). To test whether medullary DCs might not have antigen access in vivo, we injected fluorescent OVA i.v. into mice and determined its uptake by medullary and cortical DCs. More medullary than cortical DCs captured OVA under homeostatic conditions, and they also took up more filtered antigen per cell (Figure 8, C–E). On day 10 of nephritis, when the mice are heavily proteinuric, the proportion of antigen-containing cortical DCs was as high as that in medullary DCs (Figure 8, C–E). However, the antigen uptake per cell was 3-fold higher in medullary DCs than in cortical DCs (Figure 8, D and E). These findings exclude the possibility that impaired antigen uptake explains the functional defect of medullary DCs.

We next speculated that medullary DCs might function like MPs, which capture more antigen than DCs but degrade it before it can be presented to T cells (41). To test this, we offered the DCs...
DQ-OVA, which becomes fluorescent once it is cleaved. Medullary DCs cleaved somewhat more DQ-OVA than cortical DCs (Figure 8F), but this increase correlated with their higher endocytotic activity (Figure 8G). Thus, medullary DCs did not possess the high degradative activity of MPs. While the antigen-degrading enzyme cathepsin H was not differentially expressed, there was indeed less expression of invariant chain and H2-DM in medullary DCs, suggesting that medullary DCs are less well equipped to load processed antigen onto MHC-II for presentation to Th cells (Figure 8H).

Medullary DCs regulate innate immunity in the kidney. The inability of medullary DCs to activate Th cells raised the question of what physiological role these cells might play. We reasoned that their
The location might be particularly suitable for the sentinel function we recently described for kidney DCs in PN (4), because uropathogenic E. coli ascend through the collecting ducts in the medulla. To test this hypothesis, we determined DC production of the chemokine CXCL2, which attracts neutrophils into the infected kidney. Indeed, 3 hours after infection, medullary DCs produced far more CXCL2 than cortical DCs (Figure 9, A–C). MPs, identified by lack of CD11c expression, produced very little CXCL2 (Figure 9A).

We next induced PN in CX3CR1-deficient mice that possess fewer kidney DCs (Figure 1B and Figure 6D) in order to determine consequences for the anti-infectious immune response. Neutrophil numbers in CX3CR1-deficient mice were somewhat reduced at 3 hours after infection (CX3CR1+/+ mice: 81 × 10^3 ± 17 × 10^3 neutrophils per kidney; CX3CR1^GFP/GFP mice: 54 × 10^3 ± 17 × 10^3 neutrophils per kidney; P < 0.01), indicating an initial delay of neutrophil recruitment. However, at 6 hours after infection, bacterial CFUs (Figure 9D) and neutrophil numbers (Figure 9E) did not differ between CX3CR1-deficient and -competent mice. This was not because the fewer DCs in CX3CR1-deficient mice produced more CXCL2 per cell (CX3CR1^GFP/+ mice: MFI_{CXCL2} = 7,957 ± 774; CX3CR1^GFP/GFP mice: MFI_{CXCL2} = 7,948 ± 487). Instead, we found that neutrophils commenced robust CXCL2 production at 6 hours after infection (Figure 9F). This suggested that the medullary DCs in CX3CR1-deficient mice were sufficient for initiating neutrophil recruitment, and once neutrophils were present in the infected kidney, they produced large amounts of CXCL2. This production compensated for the DC deficiency in the absence of CX3CR1 with respect to antibacterial immune defense.

**Discussion**

CX3CR1 is widely used to identify APCs in various tissues, but few functional roles have been described. Here we report that CX3CR1 strongly affects the abundance of DCs, but not of MPs, in the kidney. The small intestine was the only other organ

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**Figure 8**

Medullary DCs do not process antigen for MHC-II presentation. (A) Uptake of fluorescently labeled OVA by sorted CX3CR1^+ APCs from kidney cortices (white squares) and medullas (black squares) of healthy CX3CR1^GFP/+ reporter mice. Sorted GFP^+ cells were incubated with 10 µg/ml OVA, as in A. MFI of OVA^+ cells, reflecting average amount of antigen uptake per cell. (B) Sorted cortical (white bars) and medullary (black bars) DCs from healthy or 10-day nephritic mice were incubated with 10 µg/ml OVA, as in A. MFI of OVA^+ cells, reflecting average amount of antigen uptake per cell. (C) Percentage of OVA^+ E. coli in cortex (white bars) and medulla (black bars) 30 minutes after i.v. injection of fluorescently labeled OVA into healthy or 10-day nephritic mice. (D) Representative FACS plots of the in vivo OVA uptake of cortical and medullary CD45^+MHC-II^+ cells in healthy or 10-day nephritic mice, 30 minutes after i.v. injection of Alexa Fluor 647–conjugated OVA. (E) MFI of OVA^+ cells in cortex and medulla 30 minutes upon i.v. injection of OVA, as in C. (F) MFI of cortical and medullary DCs, indicating cleaved DQ-OVA after 20 minutes of incubation with 200 µg/ml DQ-OVA. (G) Analysis of cleaved DQ-OVA per endocytosed Alexa Fluor 647–conjugated OVA in cortical and medullary DCs, after 3 hours of incubation with 25 µg/ml DQ-OVA and Alexa Fluor 647–conjugated OVA. (H) mRNA for Cathepsin H, invariant chain, and H2-DM in cortical and medullary DCs from 7-day nephritic mice, relative to GAPDH expression. Results represent 2–3 experiments, with 3 to 5 mice per group. Statistical analysis (B–E) by 1-way ANOVA with Bonferroni test or (F and H) by paired Student’s t test. *P < 0.05, **P < 0.01, ***P < 0.001.
Kidney DC numbers were reduced also in nephritic CX3CR1-deficient mice. Consequently, intrarenal DC-dependent inflammation and the course of crescentic GN were markedly attenuated in CX3CR1-deficient mice. This confirmed our previous study, in which we observed NTN attenuation after depleting kidney DCs with the use of CD11c-DTR mice (13). However, in that study, we unavoidably depleted DCs also in other tissues, which may be functionally relevant. Furthermore, CD11c-DTR mice are hampered by a side effect, bone marrow release of neutrophils and monocytes after DC depletion, which can impact immune responses, especially in PN (46). Our present findings allow conclusions regarding kidney DCs in the absence of these shortcomings. Furthermore, they suggest that targeting CX3CR1 might be useful for treating GN, especially since not only DCs, but also MPs (the DTH effector cells), were to some extent CX3CR1 dependent in kidney inflammation.

The particularly strong CX3CR1 dependence of cortical DCs in the steady state may theoretically result from an effect on precursor recruitment, their differentiation into DCs, or on DC survival/retention in the kidney. The slow turnover of kidney DCs in the steady state (42) hinders discriminating among these possibilities. Under inflammatory conditions, recruitment of DC precursors to the kidney partially depended on this CX3CR1. This is consistent with previous studies showing CX3CR1-dependent monocyte recruitment and/or survival to inflamed vessels and liver (29–31). CX3CR1+ monocytes can give rise to both DCs and MPs (5, 33). However, we have not formally shown that monocytes were the precursors of DCs in NTN. This may be doable by using CCR2-deficient mice, in which inflammatory monocytes cannot leave the bone marrow (43). Furthermore, it remained unclear why CX3CR1 selectively affected DCs, but not MPs, in homeostasis, although both cell types express this receptor. Further studies may clarify the exact ontogeny of kidney DCs in homeostasis and inflammation (44, 45).
trary, medullary DCs were superior at endocytosis, despite being “downstream” of the nephron from cortical DCs and thus further away from antigen filtered under proteinuric conditions. Instead, our findings support the interpretation that only cortical DCs processed the antigen they captured in a manner suitable to stimulate Th cells. These findings demonstrate that cortical and medullary DC functions differ.

The inability of medullary DCs to perform the hallmark DC function, activating T cells, raised the question of whether these cells can still be considered DCs. Some recent studies on intestinal APCs proposed that CD11c⁺CX3CR1⁺ cells should be generally considered MPs and that only CD103⁺CD11c⁺ phagocytes represent DCs (22, 47, 48), but this is not generally accepted (49). In contrast to the intestine, almost all DCs in the kidney are CX3CR1⁺CD11c⁺, whereas CD103⁺ DCs are a minority of less than 5% (50). We had previously classified CD11c⁺ kidney APCs as DCs, because they resembled splenic DCs in their ability to activate T cells (6). Also their transcriptome is closer to that of tissue DCs than that of MPs (7). These findings did not exclude that only a subset of kidney CD11c⁺ cells was capable of T cell activation, and here we show that only cortical CD11c⁺ cells did so, at least in NTN. We speculated that medullary CD11c⁺ cells might functionally resemble MPs, given that they captured large amounts of antigen in vivo. However, this was most likely due to the concentration of filtered antigen in the kidney medulla, which exposed cells in this compartment to higher antigen quantities. The in vitro antigen uptake of medullary DCs was only somewhat higher than that of cortical DCs. Moreover, medullary DCs did not degrade antigen too swiftly for antigen presentation, which has been stated to be characteristic of MPs (41). Instead, we found that medullary DCs were specialized at sentineling against PN. For this purpose, these DCs are strategically positioned adjacent to the collecting ducts through which UPECs first pass when they invade the kidney. In response to infection, medullary DCs rapidly produced neutrophil-attracting chemokines like CXCL2. Cortical DCs produced fewer chemokines, and MPs produced none, at least at the early time points that we examined. This sentinel function appears more compatible with the regulatory role of DCs, rather than with the immune effector functions of MPs. However, there is far more plasticity between these cell types than previously thought, especially in the kidney (51). Final classification of these APCs requires more discussion and a general consensus. For clarity, we will conclusively in the kidney (51). Final classification of these APCs requires more discussion and a general consensus. For clarity, we will conclusion.

Methods

Animals. C57/B6 mice, CX3CR1GFP/+ reporter mice, and CX3CR1GFP/GFP deficient mice were bred and kept in specific pathogen-free conditions at the animal facility of the University of Bonn. All lines had been backcrossed more than 10 times onto the C57BL/6 background.

Isolation of murine kidney DCs and OT-II cells. Complete kidneys or cortex and medulla preparations were digested with collagenase (Roche Diagnostic) and DNAse-1, as previously described (6). Tubular fragments from digested kidneys were removed by filtration. CD11c⁺ DCs were then enriched using nanobead-labeled CD11c-specific monoclonal antibodies (clone N418) (Miltenyi). Magnetic bead separation was carried out according to manufacturer’s instructions. Purity was typically 90%–95% of CD45⁻ cells. OT-II cells were isolated from spleens and lymph nodes of OT-II mice and enriched using a commercially available CD4⁺ T Cell Isolation Kit (Miltenyi). Purity was usually about 85% of CD45⁺ cells.

Flow cytometry. After treatment with Fc-blocking antibodies (clone 2.4G2), cells were stained for 15 minutes on ice with fluorochrome-labeled monoclonal antibodies against CD11c (clone HL3), I-Aβ (AF6-120.1), and CD40 (3/23) (BD Biosciences) as well as CD45 (30-F11), CD11b (M1/70), Gr1 (RB6-8C5), CD4 (GK1.5), CD3 (145-2C11), CD86 (GL1), CD80 (16-10A1), and CD103 (2E7) (eBioscience). For intracellular cytokine staining, single cell suspensions were incubated in RPMI (10% FCS) with 1 µl/ml GolgiPlug and 1 µl/ml GolgiStop (BD Biosciences) for 4 hours at 37°C. T cells were restimulated with PMA/ionomycin for 4.5 hours, starting 30 minutes before addition of GolgiPlug and GolgiStop. After cell surface staining, cells were fixed in 4% formalin (Morphisto GmbH) for 10 minutes on ice. Cell membranes were permeabilized with PermWash (BD Biosciences) for 15 minutes at room temperature. Intracellular staining was performed in PermWash for 20 minutes at room temperature using fluorochrome-labeled monoclonal antibodies against TNF-α (clone MP6-XT22), IFN-γ (XMG1.2), and IL-17 (9D1.1C8). Cells were analyzed with a BD Canto II (Becton Dickinson).

T cell activation assays. Either mice were injected with 1 mg OVA 1 hour prior to harvesting kidneys or isolated cortical and medullary DCs were loaded in vitro for 2 hours with 1 mg/ml OVA. DCs were cocultured with OT-II cells in 200 µl RPMI (10% FCS) in 96-well plates for 72 hours. T cell proliferation was measured by CFSE dilution. Therefore, isolated T cells were stained with 1 nM CFSE in PBS for 10 minutes at 37°C and washed twice with ice-cold RPMI (10% FCS). Cytokine induction was analyzed by intracellular staining of OT-II cells for IFN-γ and IL-17. Cytokines in the supernatants were measured using the Th1/Th2 10plex FlowCytomix Multiplex Kit (Bender MedSystems).

Endotoxicosis and clearance assays. For comparing the uptake of filterable antigen by cortical and medullary DCs in vivo, mice were injected with 500 ng Alexa Fluor 647-conjugated OVA (Invitrogen) per g body weight. Single cell suspensions were obtained from kidney cortices and medullas 30 minutes after antigen injection. Cells were stained and analyzed via flow cytometry. For in vitro uptake studies, cortical and medullary
DCs were sorted with a FACSDiva (Becton Dickinson). Cells were then incubated with indicated OVA concentrations for 30 minutes at 37°C, washed, and analyzed by flow cytometry. For comparing the antigen cleavage, DQ-OVA (Invitrogen), which becomes fluorescent upon cleavage, was used in addition to Alexa Fluor 647-conjugated OVA, which served as a control for antigen uptake.

**RNA preparation and RT-PCR.** RNA from FACS-sorted cortical and medullary DCs was extracted using TRIzol (Invitrogen) and Chloroform (Invitrogen) and Chlorophorm (Carl Roth) according to standard laboratory methods. Whole tissue RNA was extracted using the RNA NucleoSpin Kit (Macherey-Nagel) according to manufacturer’s instructions. RNA was reverse transcribed into cDNA using the High-Capacity Reverse Transcription Kit (Applied Biosystems). Quantitative PCR was performed for 40 cycles using SYBR Green (Applied Biosystems). The following primer sequences were used: invariant chain (forward) 5′-AGGCTTCACCTAAGAGCCACTG-3′, (reverse) 5′-ACAGAGCACCAAGTCTCAAGCCCCC-3′; H2-DM (forward) 5′-ACGTGGCTGCT-GAATGATGCT-3′, (reverse) 5′-AGGCCGTTTGCAAGGATGATT-A-3′; cathepsin H (forward) 5′-AACATGTGCTGCCGCTGTCG-3′, (reverse) 5′-TGCATACGTTGGTGGTCGCT-3′; and Cx3cl1 (forward) 5′-GCCGCGTTCTCCTATGTT-3′, (reverse) 5′-CGCACATGATTTGCGCTT-3′. All samples were run in triplicate and normalized to GAPDH or 18s rRNA.


