CD169⁺ Macrophages: Regulators of Neutrophil Trafficking to Injured Kidneys

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Ischemia-reperfusion injury (IRI) is a major cause of AKI. Despite increasing knowledge of the multifactorial pathophysiology of IRI, which includes epithelial and endothelial cell injury, inflammatory cell responses, and generation of soluble mediators, there is no effective treatment except for supportive care. Inflammation is well established as a driving force that initiates injury and is increasingly implicated in the long-term sequelae of AKI. The inflammatory response during IRI includes proinflammatory cytokine release, endothelial cell activation, and tissue infiltration by neutrophils, macrophages, and lymphocytes. Several reports demonstrated that depletion or blockage of leukocytes ameliorates the inflammatory response but can also be detrimental in some cases. Although monocytes/macrophages and neutrophils are known to be critical effectors of the inflammatory response, further dissection of their early molecular events during AKI is critical for clarifying their roles and developing novel therapeutic strategies. In this issue of JASN, Karasawa et al. have identified a subset of peripheral blood monocytes and kidney-resident F4/80⁺ macrophages, categorized as CX3CR1hiLy6ClowCD169⁺ cells, that suppress the excessive activation of endothelial cells and neutrophil infiltration in IRI kidneys.

Neutrophil infiltration occurs in ischemic kidneys within the early few hours of reperfusion, which has primarily been demonstrated in experimental models. Neutrophils exacerbate ischemic injury through blockage of capillaries (no-reflow phenomenon), release of reactive oxygen species and inflammatory cytokines including IFN-γ and IL-17, and disrupting the endothelial and epithelial barriers during their transmigration into the interstitial compartment. Depletion of neutrophils, as well as blocking neutrophil transmigration to the kidney, can improve tissue damage after IRI, although some studies have failed to demonstrate a protective effect.

Recruitment and transendothelial migration of neutrophils in capillary venules is a key event in the inflammatory response against tissue damage. Although the precise regulation of this process is incompletely understood, a cascade of interactions occurring between blood-borne neutrophils and the endothelium (characterized by rolling, firm adhesion, and extravasation) is required for neutrophil recruitment to the inflammation site. Resident dendritic cells play an important role in neutrophil recruitment by generating a potent chemotactic gradient with the release of TNF-α, IL-6, monocyte chemotactic protein 1, regulated on activation, normal T cell expressed and secreted (RANTES), macrophage inflammatory protein 2, and keratinocyte-derived chemokine (the mouse analog of human IL-8). IL-8 plays a crucial role in neutrophil recruitment and mediates tissue injury via cytokines, free radical intermediates, and proteases.

Another key event in neutrophil recruitment is endothelial cell activation, which leads to an increase in vascular permeability and upregulation of adhesion molecules such as intercellular adhesion molecule 1 (ICAM-1) and P-Selectin. These molecules facilitate neutrophil adhesion to endothelial cells and their extravasation, especially in the outer medullary region. A key role for ICAM-1 in IRI-induced inflammation has been established by a number of studies using mice deficient for ICAM-1 or blockade of ICAM-1 in wild-type (WT) animals. A role for tissue-resident macrophages and for the perivascular subset of macrophages in neutrophil recruitment was recently implicated in the induction of tissue inflammation.

Monocyte/macrophage lineage expresses several surface markers, including CD11b, CD11c, F4/80, Ly6C, and CX3CR1. These markers can be simultaneously expressed in both pro- and anti-inflammatory monocytes/macrophages and/or bone marrow–derived and kidney-resident monocytes/macrophages in specific disease states. The two distinct subsets of peripheral monocytes differ in their expression levels of CX3CR1 and Ly6C. CX3CR1hiLy6Clo monocytes patrol the surface of endothelial cells to maintain endothelial integrity, whereas the CX3CR1hiLy6Clo monocytes are recruited selectively to the inflamed tissue where they differentiate into macrophages and dendritic cells.

CD169, sialic acid–binding IgG-like lectin (Siglec)-1, originally referred to as a lectin-like receptor, is a unique cell surface receptor of macrophages. CD169⁺ macrophages during health are mainly present in secondary lymphoid organs, such as the lymph node and spleen. However, during disease, they are found in many other organs and can serve as a regulator of adaptive immunity through the activation of T and B cells.
as well as antigen presentation.\textsuperscript{11} CD169\textsuperscript{+} macrophages have been associated with the progression of inflammation-related diseases, including arthritis and GN\textsuperscript{11}, and the precise mechanisms remain undefined.

Although the presence of CD169\textsuperscript{+} macrophages, referred to as Siglec-1\textsuperscript{+} macrophages, was previously reported,\textsuperscript{12} their role in kidney diseases is relatively unknown. In this issue of JASN, Karasawa \textit{et al.} report the novel finding that CD169\textsuperscript{+} macrophages, derived from CX3CR1\textsuperscript{+} monocytes and referred to as CX3CR1\textsuperscript{hi}Ly6C\textsuperscript{lo}CD169\textsuperscript{+} cells, protect the kidney from ischemic AKI.\textsuperscript{2} Compared with controls, depletion of the CD169\textsuperscript{+} macrophages by diptheria toxin resulted in more severe IRI-induced tubular necrosis and functional impairment, as well as higher mortality. To define the origin of the CD169\textsuperscript{+} macrophage, an elegant parabiosis model (surgically joining together two organisms which leads to shared circulatory system) was established using CD169-cre-YFP and ROSA26-YFP mice, which demonstrated that a significant portion of the CD169\textsuperscript{+} macrophages reside in the kidney and only a minor portion were derived from the circulating monocyte population. In addition, Karasawa \textit{et al.} found that kidney-resident CD169\textsuperscript{+} macrophages reside along the vasculature, similar to pericytes, suggesting a role for maintaining the vascular integrity.\textsuperscript{2} IRI results in enhanced vascular permeability due to the disintegration of the junctional barrier between endothelial cells, which contributes to the recruitment of leukocytes into the injured kidney. Indeed, deletion of the CD169\textsuperscript{+} monocytes/macrophages exacerbated recruitment of neutrophils into the kidney after IRI. The primary mechanism for the increased neutrophil recruitment into injured tissue was due to elevated expression of endothelial ICAM-1, as well as an increase of chemokine (C-X-C motif) ligands CXCL1 and CXCL2. Blockage of ICAM-1 using an ICAM-1–specific antibody prevented IRI-induced lethality in mice, confirming its important role. In \textit{vitro} experiments were conducted to determine whether CD169\textsuperscript{+} monocytes/macrophages may require direct interaction with endothelial cells to regulate ICAM-1 expression. During \textit{in vitro} coculture experiments with leukocytes and endothelial cells seeded together, but not in transwell cultures, leukocytes from CD169-deleted mice markedly increased the expression of ICAM-1. This demonstrated the requirement for a direct interaction of leukocytes and endothelial cells in ICAM-1 upregulation.

To further elucidate details of this protective leukocyte population during AKI, total PBMCs were transferred into CD169-deleted mice before IRI. The survival rate of CD169-DTR mice from lethal AKI improved by 60%, whereas the injection of WT Ly6G\textsuperscript{hi} neutrophils did not improve the survival rate.\textsuperscript{2} Furthermore, transfer of the fractionated Ly6C\textsuperscript{lo} monocyte subtype into CD169-deleted mice improved the survival rate of the mice from kidney IRI compared with the same mice without transfer. Unexpectedly, Ly6C\textsuperscript{hi} monocytes, considered an inflammatory monocyte, also showed mild protection from IRI. It is suggested that the protective effect of Ly6C\textsuperscript{hi} monocytes may be due to switching to Ly6C\textsuperscript{lo} monocytes, although further study is warranted to confirm this postulate. The monocyte transfer was associated with the suppression of ICAM-1, further confirming suppression of endothelial cell activation by subtype-specific monocytes/macrophages in kidney IRI. These data concur with a recently reported study in which perivascular macrophages directly affect the adhesive and transmigratory activity of blood neutrophils.\textsuperscript{13}

Nonetheless, important issues remain to be addressed, including the question of whether CD169\textsuperscript{+} monocyte transfer would be protective in the setting of IRI in WT mice, which could pave the way to translate the findings to humans. Recent reports showed that some monocyte/macrophage subsets, such as Ly6C\textsuperscript{lo}, are required for the prevention and recovery from acute injury in several tissues, including the kidney.\textsuperscript{14,15} The kidney function of WT mice recovered at 48 hours post-IRI, whereas that of CD169\textsuperscript{+} macrophage-depleted mice deteriorated.\textsuperscript{3} The functional impairment observed at 48 hours after IRI by CD169\textsuperscript{+} macrophage depletion could be associated with the impairment of repair process, as well as early injury. This possibility is further supported by the observation that after unilateral IRI in CD169\textsuperscript{+} macrophage-depleted mice, tubular regeneration was impaired after 7 days, suggesting a possible role for CD169\textsuperscript{+} macrophages in recovery after IRI. It should also be mentioned that renal resident and/or infiltrating monocytes, macrophages, and dendritic cells have overlapping phenotypes and surface marker expression. Because the CD169\textsuperscript{+} macrophage was positive for Ly6C, a marker of dendritic cells, investigating the role of CD169\textsuperscript{+}Ly6C\textsuperscript{+} dendritic cells would also be of interest in AKI.

In summary, the elegant mechanistic findings of Karasawa \textit{et al.} demonstrate the role of the CD169\textsuperscript{+} macrophage as a regulator of neutrophil recruitment and vascular homeostasis in ischemic kidneys.\textsuperscript{2} Better understanding of the CD169\textsuperscript{+} monocyte/macrophage functions, tissue factors that may trigger their activation, and the macrophage effectors that may activate endothelial cells may provide novel treatment strategies for ischemic AKI.

**DISCLOSURES**

None.

**REFERENCES**