Lupus Nephritis: From Pathogenesis to Targets for Biologic Treatment

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Immune complex · Belimumab · Interferon · Systemic lupus erythematosus · Abatacept · Proteinuria

Abstract
Background/Aims: Lupus nephritis is an organ manifestation of systemic autoimmunity. Current treatment algorithms are still based on unselective immunosuppressive drugs. There is hope that highly selective biological drugs could be as or even more effective but less toxic. A profound understanding of the pathogenesis of lupus nephritis is necessary to identify the optimal molecular targets. Methods: PubMed and www.clinicaltrials.gov were searched using ‘lupus nephritis’ as the key word. Results: The pathogenesis of lupus nephritis is based (1) on the mechanisms that lead to loss of tolerance against nuclear autoantigens, i.e. systemic lupus, and then (2) on the mechanisms of immune complex-induced intrarenal inflammation. Systemic lupus develops when genetic variants allow autoimmunization against nuclear autoantigens, e.g. by impairing lymphocyte depletion via apoptosis, opsonization, and rapid phagocytic clearance. This allows endogenous nucleic acids to directly activate Toll-like receptors on dendritic cells or B cells, a process that drives IFN-α-driven immunity, antigen presentation, and the activation of autoreactive lymphocyte subsets. Activation of B cells and their maturation to plasma cells promotes autoantibody production and subsequent immune complex glomerulonephritis. Complement and numerous proinflammatory cytokines drive the inflammatory process that can cause kidney injury, scarring, and chronic kidney disease. Conclusion: Systemic lupus is more a variable syndrome than a single disorder based on heterogeneous genetic variants and complex aberrant immune alterations. This makes it less likely that a single specific biological drug will be as efficient as currently used unselective immunosuppressive drugs. Autoantibody production and intrarenal immune complex formation are the hallmark of lupus nephritis. However, kidney injury and scarring also result from local amplification of tissue inflammation. Therefore, a combination of unselective immunosuppressive and biological drugs that block immune cell recruitment or proinflammatory cytokines may be promising to improve disease outcomes in lupus nephritis.

Introduction

Biological drugs have significantly improved outcomes in many autoimmune disorders, but so far clinical trials have failed to demonstrate any significant benefit of biological drugs in lupus nephritis. This is surpris-
ing because all autoimmune disorders, including systemic lupus erythematosus (SLE), are based on antigen-presenting cells that trigger the activation and proliferation of autoreactive lymphocyte subsets. So what distinguishes the pathogenesis of SLE from other autoimmune disorders? Why do clinical trials often fail to validate drug efficacy previously demonstrated in preclinical experiments or uncontrolled cohort studies? Disease heterogeneity is an important factor that distinguishes SLE from other autoimmune disorders and which remains a challenge for clinical trial design. Genome-wide association studies have documented that numerous different genetic alterations, each of them conferring only a minor risk contribution, are present in SLE patients. This implies that SLE is rather a clinical syndrome that develops from different combinations of genetic alterations that cause systemic autoimmunity through different avenues of immune dysregulation. This may explain why some but not all patients benefit from biological drugs that modulate highly selective targets. Nonetheless, to move beyond unselective immunosuppressive drugs in lupus nephritis management, it is necessary to identify common pathways in the pathogenesis of SLE and lupus nephritis. In this review, we briefly summarize current concepts of disease pathogenesis in SLE and lupus nephritis in detail elsewhere [1], only a brief summary is provided here (table 1).

### Pathogenesis of SLE and Lupus Nephritis

As we have recently described the current pathogenic concepts of SLE and lupus nephritis in detail elsewhere [1], only a brief summary is provided here (table 1).

#### Table 1. Pathomechanisms in SLE and lupus nephritis

<table>
<thead>
<tr>
<th>Pathomechanisms of autoimmunity outside the kidney</th>
<th>Pathomechanisms of lupus nephritis inside the kidney</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impaired silent cell death and dead cell removal</td>
<td>Immune complex formation and classical complement pathway activation</td>
</tr>
<tr>
<td>Nuclear particles mimic viruses at viral recognition receptors of the innate immune system</td>
<td>Mesangial vs. subendothelial vs. subepithelial immune complexes</td>
</tr>
<tr>
<td>Antiviral immunity</td>
<td>Intrarenal induction of cytokines, chemokines, and adhesion molecules recruits leukocytes</td>
</tr>
<tr>
<td>Autovaccination leading to persistent antinuclear antibody production</td>
<td>Tertiary lymphoid organ formation inside the kidney, i.e. local immunoglobulin production</td>
</tr>
<tr>
<td>Flares triggered by transient autoantigen loads or unselective immune activation</td>
<td>Insufficient regeneration and tissue scarring</td>
</tr>
</tbody>
</table>

### Systemic Autoimmunity in SLE

SLE develops from a loss-of-tolerance for nuclear autoantigens as is evident from the presence of antinuclear antibodies. As tolerance against cell nuclei is normally assured by numerous mechanisms and genes, many different combinations of genetic and environmental factors can break tolerance, cause antinuclear antibody positivity, and eventually trigger SLE. The major checkpoints of immune dysregulation are described in table 1 and below.

**Impaired Silent Cell Death and Dead Cell Removal.** Genetic variants that impair physiological (immunologically silent) suicide of autoreactive lymphocytes during negative selection in lymphoid organs drive secondary necrosis and the release of nuclear material into the extracellular space. Similarly, this is also the case with environmentally induced tissue cell necrosis, e.g. a sunburn or a trauma increases the amount of extracellular nuclear material. In SLE, often genetic variants that impair the phagocytic clearance of such extracellular nuclear particles keep nuclear particles in the extracellular space [2]. For example, insufficient phagocytic clearance of extracellular neutrophil traps contributes to this phenomenon [3].

**Nuclear Particles Trigger Antiviral Immunity via Innate Viral Recognition Receptors.** Extracellular nuclear particles share structural and molecular similarities with viral particles and their nucleic acid components can activate dendritic cells and B cells via Toll-like receptors 7 and 9 [4]. This specifically triggers the induction of interferon-α and subsequently a ‘pseudo’ antiviral immune response, which accounts for unspecific symptoms of SLE including fatigue, fever, myalgia, and arthralgia [5].

**Autovaccination Leads to Persistent Antinuclear Antibody Production.** Because nuclear autoantigens are pre-
sent in the context of innate immune activation, induced costimulation promotes the activation of T and B cell subsets with specificities for nuclear autoantigens. This process involves B cell maturation and differentiation into plasma cells that produce antinuclear antibodies. Memory T cells and bone marrow long-lived plasma cells assure lifelong immune memory, which cannot be eradicated by standard therapies conceptually like immune memory obtained by previous vaccinations [6]. Unspecific lymphoproliferation drives lymphadenopathy as a manifestation of SLE.

**Incident Cell Necrosis or Unspecific Immune Activation Trigger SLE Flares.** Sudden massive cell death (sunburn or trauma) or exposure to immunostimulatory agents (e.g. during infections) mimic antigen re-exposure or provide unspecific stimuli of innate and adaptive immunity that may expand autoreactive lymphocyte clones and cause a SLE flare [7].

**Intrarenal Pathomechanisms of SLE-Related Nephritis Immune Complex Formation and Classical Complement Pathway Activation.** Lupus nephritis does not develop in the absence of antinuclear antibodies [8]. Circulating polyclonal autoantibodies bind to intrarenal nucleosomes and other autoantigens, which leads to local complement activation, cell injury, and subsequent cytokine and chemokine secretion.

**The Immune Complex Formation Site Determines Lupus Nephritis Outcomes.** The polyclonal lupus autoantibody isotypes can localize to different compartments within the glomerulus, which affects the type of histopathological lesion as well as the alterations of glomerular function [9]. Immune complex formation in the mesangium induces mesangiproliferative glomerulonephritis (lupus nephritis classes I and II), which is often mild and rarely progresses to end-stage kidney disease. Subendothelial immune complex formation (lupus nephritis classes III and IV) causes vascular obstruction by endothelial cell swelling and clotting, which promotes a decline of glomerular filtration rate. Vascular necrosis and glomerular basement membrane ruptures promote hematocrit, crescent formation, and subsequently glomerulosclerosis. Subepithelial immune complex formation (membranous lupus nephritis class V) injures podocytes, which promotes massive proteinuria and podocyte loss-related glomerulosclerosis.

**Induction of Cytokines, Chemokines, and Adhesion Molecules Recruits Leukocytes.** Leukocyte recruitment amplifies intrarenal inflammation and promotes secondary tissue injury related to tissue inflammation and drives a vicious cycle of inflammation-induced tissue injury and injury-related inflammation. To target this pathomechanism, anti-inflammatory drugs that do not cause global immunosuppression may be sufficient.

**Tertiary Lymphoid Organ Formation inside the Kidney.** Local expression of lymphotoxin and homeostatic chemokines drives tertiary lymphoid organ formation at sites of chronic inflammation to promote the (auto-) immune response, e.g. by local autoantibody production.

**Insufficient Regeneration and Tissue Scarring.** Attempts to heal tissue injury often create new lesions. Lesions of hyperactive repair include hyperproliferation of mesangial cells (mesangiproliferative lupus nephritis), endothelial cells (endocapillary lupus nephritis), and parietal epithelial cells (crenscient lupus nephritis). Lesions of insufficient repair include podocyte loss-related scarring (FSGS and glomerulosclerosis).

**Therapeutic Targets for (Biological) Drugs**

The current management of lupus nephritis remains based on steroids, cyclophosphamide, azathioprine, and mycophenolate mofetil, which are all unselective immunosuppressive drugs that suppress multiple components of adaptive immunity [10]. These drugs have proven to be efficient in reducing lupus nephritis disease activity, but the long-term outcomes of lupus nephritis have not further improved during the last 30 years. Unselective immunosuppressive drugs are associated with potentially life-threatening infectious complications. Therefore, it remains an unmet medical need to develop new drugs that more specifically interfere with the pathomechanisms of SLE and cause less side effects [11]. In the following we discuss several targets of interest and provide the rationale to explore them for the treatment of lupus nephritis (fig. 1). Past or ongoing clinical trials with target-related drugs are listed in table 2.

**Aberrant Cell Death and Insufficient Clearance of Dead Cells**

Currently no biological drugs are available that specifically control this aspect of lupus pathogenesis. The prevention of sunburns by avoiding UV light exposure and using sunscreen remains important.

**Immunostimulatory Effects of Endogenous Nucleic Acids and IFN-α-Mediated Immunity**

Toll-like receptor 7/9 blockade can suppress nucleic acid autoadjuvant-driven disease activity of lupus nephri-
Table 2. Biological drugs for lupus nephritis listed in www.clinicaltrials.gov

<table>
<thead>
<tr>
<th>Target</th>
<th>Drug name</th>
<th>Trial phase</th>
<th>Trial status</th>
<th>Duration, months</th>
<th>Nephritis class</th>
<th>NCT number</th>
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<td>III, IV, V</td>
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<td>III, IV</td>
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</table>

Fig. 1. Pathomechanisms and treatment targets in lupus nephritis. 

a Genetic variants of homeostatic lymphocyte death and of the rapid clearance of dead cells predispose to necrotic cell death and a persistence of nuclear particles in the extracellular space. No specific treatments are available at present for this aspect of lupus pathogenesis. The avoidance of sun burns and toxin exposure can help to prevent disease flares triggered by incident episodes of massive cell death. 

b Extracellular nuclear particles containing autoadjuvants like CpG-DNA or immunostimulatory RNA together with other Toll-like receptor ligands released by dead cells activate antigen-presenting cells (dendritic cells and B cells) to present autoantigens together with costimulatory molecules. This process leads to an immune interpretation of the autoantigen as ‘foreign’ and triggers an adaptive immune response, e.g. autoantigen-specific T and B cells. Several biological drugs intend to interfere with this pathomechanism. 

c Circulating autoantibodies bind to their respective autoantigens within the kidney, a process referred to as in situ immune complex formation. This activates complement and other inflammatory mediators that can be targeted with biological drugs to control renal inflammation. IFN-γ, MHC I, MHC II (major histocompatibility complex), TNF, and BAFF/BLyS.  

(For figure see next page.)
vents lupus nephritis in animal models which suppresses IgG autoantibody production and pre-
rents lupus nephritis classes III–V, but the respective antagonists that are to be tested in clinical trials are more based on nucleic acid for-
\[12, 13\], but the randomized placebo-controlled LUNAR trial could not demonstrate any ben-
\[14\]. CD40 and CD40L also promote costimulation, but three trials with anti-CD40L failed to demonstrate efficacy. Abetimus is a drug that modulates autoimmunity via an-
tegen-presenting cells and CD28 on T cells efficiently sup-
Mizrelizumab was reported to meet the primary composite endpoint in a phase 2b trial of nonrenal lupus patients. Data on its efficacy on lupus nephritis are not yet available.

**Autoantigen Presentation and T Cell Activation**

The processing and presentation of autoantigens in the context of costimulation is at the center of every au-
tigen-presenting cells and CD28 on T cells efficiently sup-
suppresses alloimmune T cell activation after kidney trans-
\[15\]. B cells clearly contribute to SLE and lupus nephritis, which provides a rationale for the use of drugs that de-
plete CD20+ B cells and short-lived plasma cells such as rituximab, ocrelizumab, or ofatumumab. Uncontrolled studies on refractory lupus nephritis documented re-
response rates of 75% [16], but the randomized placebo-
controlled LUNAR trial could not demonstrate any ben-
efice of add-on rituximab on top of a profound immuno-
suppressive regimen for the induction therapy of incident lupus nephritis classes III–V [17]. However, the clinical efficacy of off-label rituximab use by many centers has maintained the interest in B cell ablation in lupus nephri-
tis. Based on uncontrolled efficacy data of rituximab monotherapy after methylprednisolone pulsing, the RITUXILUP trial will further test the concept of B cell ablation controlling severe lupus nephritis [18]. CD22 is a 135-kDa B cell-specific transmembrane sialoglycopro-
tein that is expressed at the cell surface on mature IgM+ IgD+ B cells, but absent on plasma cells and memory B cells. Blocking CD22 with epratuzumab depletes naïve and transitional B cells via antibody-dependent cellular cytotoxicity, which lowers peripheral B cell counts by 40%. This effect can improve moderate-to-severe nonre-
nal flares in SLE patients, but efficacy data on lupus nephritis are not yet available [19]. BLyS (B lymphocyte stimulator) is a B cell survival factor that can be blocked with belimumab. Large randomized placebo-controlled trials have proven that add-on belimumab on top of stan-
dard maintenance therapy can significantly reduce per-
sistent SLE activity [20], which has led to FDA and EMA approval of belimumab for the maintenance therapy of nonrenal lupus in the USA and Europe. Severe lupus ne-
phritis patients were excluded in the BLISS-56 and BLISS-76 trials, but data from patients with moderate ne-
phritis raise hope that belimumab can also be efficient in severe lupus nephritis [21]. Such a trial is currently re-
cruiting patients. Other B cell-directed biological drugs include the recombinant TACI-human IgG fusion pro-
tein atacicept, the BAFF-blocking antibody LY2127399, and a BAFF-receptor antibody [22].

**Long-Lived Plasma Cells**

Targeting long-lived plasma cells offers the potential of directly modulating antibody-producing cells that maintain humoral immune memory [6]. These cells re-
side in survival niches in the bone marrow and in tertiary lymphoid organs within the inflamed tissue. They can be targeted by antithymocyte globulin, small molecule pro-
teasome inhibitors, anti-CD138/CD38 antibodies, or by targeting BLyMP-1. Data from clinical trials that have tested related biological drugs in lupus nephritis are not yet available [6].

**Mediators of Tissue Inflammation**

Tissue inflammation involves numerous proinflam-
\[18\]. CD22 is
\[19\]. BLyS
\[20\]. BLISS-56
\[21\]. BLISS-76
\[22\].
\[23\]. The trans-

Pathogenesis of Lupus Nephritis

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229
continental ATLAS trial that tests TWEAK blockade in the remission phase of lupus nephritis is still ongoing. Macrophage-dependent inflammation is targeted by anti-macrophage inhibitory factor IgG, for which a safety study in lupus nephritis patients has been completed. Also the CCL2-CCR2 axis is a promising target to limit macrophage-dependent inflammation. Preclinical experiments suggest that adding a CCL2 inhibitor to a low dose of cyclophosphamide is as efficient as high-dose cyclophosphamide, but avoids myelosuppression and lymphocyte ablation [24]. A first trial documented a positive effect on proteinuria using bindarit as a blocker of this pathway [25].

Summary

Lupus nephritis develops from extrarenal and intrarenal pathomechanisms. The extrarenal factors include complex combinations of genetic variants in numerous immune pathways that are different in each patient, which may affect success rates of very selective biological drugs in clinical trials. Therefore, treating lupus nephritis with a monotherapy of a selective biological drug should be challenging. Unselective immunosuppressive drugs may remain necessary to suppress the complex interplay of the numerous immune cell subsets that contribute to humoral and cellular autoimmunity in SLE. Lupus nephritis, however, is a classic immune complex glomerulonephritis involving complement-mediated renal inflammation, amplified by infiltrating leukocytes and driven by numerous proinflammatory cytokines. Inflammation-related kidney injury and tissue remodeling cause renal dysfunction and chronic kidney disease in lupus. Therefore, anti-inflammatory biological drugs that limit tissue injury should be attractive combination partners for unselective immunosuppressive drugs that control systemic autoimmunity.

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References


