Effector mechanisms of ANCA-associated glomerulonephritis
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Chapter 4

IgG glycan hydrolysis attenuates ANCA-mediated glomerulonephritis

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ABSTRACT
Anti-neutrophil cytoplasmic autoantibodies (ANCA) directed against myeloperoxidase (MPO) and proteinase 3 (Pr3) are considered pathogenic in ANCA-associated necrotizing and crescentic glomerulonephritis (NCGN) and vasculitis. Modulation of ANCA IgG glycosylation may potentially reduce its pathogenicity by abolishing Fc receptor-mediated activation of leukocytes and complement. Here, we investigated whether IgG hydrolysis by the bacterial enzyme endo-glycosidase S (EndoS) attenuates ANCA-mediated NCGN. In vitro, treatment of ANCA IgG with EndoS significantly attenuated ANCA-mediated neutrophil activation without affecting antigen-binding capacity. In a mouse model of anti-MPO IgG/LPS-induced NCGN, we induced disease with either unmodified or EndoS-treated (deglycosylated) anti-MPO IgG. In separate experiments, we administered EndoS systemically after disease induction with unmodified anti-MPO IgG. Pretreatment of anti-MPO IgG with EndoS reduced hematuria, leukocyturia, and albuminuria and attenuated both neutrophil influx and formation of glomerular crescents. After inducing disease with unmodified anti-MPO IgG, systemic treatment with EndoS reduced albuminuria and glomerular crescent formation when initiated after 3 but not 24 hours. In conclusion, IgG glycan hydrolysis by EndoS attenuates ANCA-induced neutrophil activation in vitro and prevents induction of anti-MPO IgG/LPS-mediated NCGN in vivo. Systemic treatment with EndoS early after disease induction attenuates the development of disease. Thus, modulation of IgG glycosylation is a promising strategy to interfere with ANCA-mediated inflammatory processes.
INTRODUCTION

Wegener’s granulomatosis, microscopic polyangiitis, Churg-Strauss syndrome, and idiopathic pauci-immune necrotizing and crescentic glomerulonephritis (NCGN) are forms of small-vessel vasculitis that are strongly associated with anti-neutrophil cytoplasmic autoantibodies (ANCA).\textsuperscript{1} ANCA comprise a group of autoantibodies directed against lysosomal proteins of neutrophils and monocytes. The primary target antigens are proteinase 3 (Pr3) and myeloperoxidase (MPO).\textsuperscript{2} ANCA-associated systemic vasculitides are severe diseases with a high mortality rate when left untreated. Current treatment regimens are associated with significant adverse effects without preventing the occurrence of relapses\textsuperscript{3}; therefore, more effective and less toxic therapeutic approaches are needed.

Similar to autoantibodies in other autoimmune diseases, ANCA are considered to be pathogenic.\textsuperscript{4} The pathogenic effect of ANCA comprises activation of cytokine-primed neutrophils within the microvasculature, through binding of ANCA IgG to surface-expressed antigens with their F(\text{ab'})\textsubscript{2} portions and ligating to constitutively expressed neutrophil Fcγ receptors (FcγRI, FcγRIIa and FcγRIIIb), with their Fc tail.\textsuperscript{5,7} The activated neutrophils release their granules, which contain tissue-degrading enzymes, and generate oxygen radicals, leading to bystander damage of endothelial cells. In addition, the alternative complement pathway is activated and the recruitment of neutrophils and monocytes is promoted, resulting in accelerated inflammation and eventually organ damage.\textsuperscript{4} The pathogenicity of ANCA is most convincingly proven by the finding that administration of murine anti-MPO antibodies to mice induces an acute glomerular inflammation that progresses to NCGN within days.\textsuperscript{8} Subsequent studies have shown that anti-MPO IgG-mediated NCGN in this model is severely aggravated upon co-administration of lipopolysaccharide (LPS), requires neutrophils as the main effector cells, and is complement and Fc receptor dependent.\textsuperscript{9-12}

To function properly, IgG molecules require glycosylation of a conserved asparagine residue (Asn297) in the CH\textsubscript{2} domains of both heavy chains of the Fc fragment. These Fc glycans are complex biantennary structures with a high degree of heterogeneity, depending on species, age, gender, and disease status.\textsuperscript{13} Modifications in the Fc glycans cause conformational changes of the IgG molecule, which affect the affinity of the Fc fragment for binding to FcγRs and complement factor C1q. Complete removal of the Fc glycans by glycoside hydrolases abolishes Fc-mediated effector functions, such as antibody-dependent cell-mediated cytotoxicity and complement-dependent cytotoxicity. IgG glycan hydrolysis is therefore a promising strategy for the treatment of (auto) antibody-mediated diseases.

Endoglycosidase S (EndoS) secreted by \textit{Streptococcus pyogenes} specifically hydrolyzes the conserved asparagine-linked glycans on the IgG heavy chains.\textsuperscript{14,15} EndoS hydrolyzes all subclasses of human IgG and almost completely abolishes IgG binding to FcγRs and IgG-dependent complement activation.\textsuperscript{16} \textit{In vivo}, administration of EndoS to mice causes complete hydrolysis of circulating IgG within hours that lasts for several days.\textsuperscript{17} Importantly, \textit{in vivo} EndoS administration does not affect glycosylated plasma proteins other than IgG and has no detectable adverse effects. Moreover, repeated EndoS injections induce only a minimal immune response against the enzyme that
does not affect its activity.\textsuperscript{15} Interestingly, pretreatment of pathogenic autoantibodies with EndoS abrogates disease development in mouse models of arthritis and immune thrombocytopenic purpura.\textsuperscript{15,18} Systemic injection of EndoS also rescues mice from already established immune thrombocytopenic purpura and inhibits pathology in lupus-prone mice.\textsuperscript{15,17}

We hypothesized that Fc glycans of ANCA IgG are important for the development of ANCA-associated glomerulonephritis/vasculitis and that glycan hydrolysis by EndoS abrogates the pathogenic effects of ANCA. To test this hypothesis, we evaluated whether EndoS treatment inhibits ANCA IgG-induced neutrophil activation \textit{in vitro}. Furthermore, we investigated whether EndoS (pre)treatment diminishes glomerulonephritis development in experimental anti-MPO antibody/LPS-induced NCGN.

\section*{MATERIALS AND METHODS}

\subsection*{Preparation of IgG fractions from ANCA-positive patients and control subjects}

Plasma samples, obtained from plasmapheresis material or freshly drawn blood, were collected from ANCA-positive patients with active, biopsy-proven NCGN (MPO positive \(n = 5\), Pr3 positive \(n = 6\), five of which are used in each assay). The patients received immunosuppressive treatment. Also, plasma samples from patients with anti-glomerular basement membrane disease and from healthy control subjects were collected (characteristics are shown in Table 1). Plasma samples were

\begin{center}
\begin{tabular}{llll}
\textbf{Parameter} & \textbf{ANCA specificity} & \textbf{ANCA titer} & \textbf{Gender} & \textbf{Age (years)} \\
Patients & & & & \\
1 & Anti-MPO & 160 & M & 66 \\
2 & Anti-MPO & 320 & F & 23 \\
3 & Anti-MPO & 80 & M & 43 \\
4 & Anti-MPO & 320 & M & 56 \\
5 & Anti-MPO & 80 & F & 73 \\
6 & Anti-Pr3 & 160 & M & 66 \\
7 & Anti-Pr3 & 320 & M & 66 \\
8 & Anti-Pr3 & 320 & M & 48 \\
9 & Anti-Pr3 & 80 & M & 34 \\
10 & Anti-Pr3 & 40 & F & 28 \\
11 & Anti-Pr3 & >640 & F & 73 \\
Controls & Antibodies & & & \\
1 & Anti-GBM & Negative & F & 35 \\
2 & Anti-GBM & Negative & M & 42 \\
3 & None & Negative & F & 60 \\
4 & None & Negative & M & 50 \\
5 & None & Negative & M & 55 \\
\end{tabular}
\end{center}

GBM, glomerular basement membrane.
tested for the presence of anti-Pr3 or anti-MPO antibodies by capture ELISA. Plasma samples were tested for ANCA titers by indirect immunofluorescence assay on ethanol-fixed neutrophils. Until IgG isolation, the plasma samples were stored at -20°C. Purified IgG fractions were prepared using a protein G column (Hi-Trap Protein G HP; GE Healthcare, Freiburg, Germany) according to the manufacturer's instructions. Before use in the activation experiments, the IgG fractions were centrifuged for 15 min at 14000 x g to remove aggregates.

**EndoS treatment of patient ANCA IgG**

Recombinant EndoS was produced in *Escherichia coli* and purified *via* a GST affinity tag as described previously. For all experiments, recombinant GST-tagged EndoS (GST-EndoS) or GST alone was used. For *in vitro* experiments, 100 μg of ANCA IgG was incubated with 1 μg of GST-EndoS in PBS at 37°C for 2h. The efficiency of GST-EndoS treatment was analyzed by SDS-PAGE and LCA blotting as described under Analysis of IgG glycan hydrolysis.

**Analysis of IgG glycan hydrolysis**

Two or 0.5 μg of purified IgG was separated on 10% SDS-PAGE and stained with Coomassie blue or electroblotted onto polyvinylidene difluoride membrane (Immobilon-P; Millipore, Bedford, MA), respectively. Glycosylated IgG was detected by using 1 μg/ml of biotinylated LCA and 1 μg/ml of streptavidin-horseradish peroxidase (Vector Laboratories, Burlingame, CA) and SuperSignal West Pico peroxidase substrate (Pierce, Rockford, IL). Membranes were analyzed using a Chemidoc XRS imaging system and Quantity One image analysis software (Bio-Rad, Hercules, CA).

**Indirect immunofluorescence**

Freshly isolated healthy donor neutrophils were ethanol-fixed and sequentially incubated with ANCA IgG fractions (dilutions 1:20 to 1:640) and affinity purified F(ab')2 rabbit anti-human IgG/FITC (diluted 1:400; Dako A/S, Copenhagen, Denmark) using a standard protocol.

**Human anti-MPO and anti-Pr3 ELISA**

Untreated, GST-EndoS- or GST control-treated ANCA IgG fractions were tested for the ability to bind to Pr3 or MPO by ELISA. Briefly, Nunc Maxisorp plates were coated with 135 μg/ml MPO or 10 μg/ml Pr3 (in the presence of 87 μg/ml PMSF) in 0.1 M carbonate buffer (pH 9.6) overnight at 4°C. After washing thoroughly with 25 mM Tris/HCl (pH 8.0) containing 0.15 M NaCl and 0.05% Tween-20 (washing buffer), the plates were incubated with 100 μl of IgG fractions (two-fold serial dilutions from 1:25 to 1:3200) in 50 mM Tris/HCl (pH 8.0) containing 0.25% Tween-20, 0.30 M NaCl, and 1% BSA (incubation buffer) for 2 h at room temperature. After washing, bound antibody was detected by incubation with 167 ng/ml affinity-purified F(ab')2 goat anti-human IgG linked to alkaline phosphatase (American Qualex, San Clemente, CA), and p-nitrophenyl-phosphate disodium was used as a substrate. The OD at 405 nm was measured.
Isolation of neutrophils

Neutrophils were isolated from heparinized venous blood of healthy controls by centrifugation on Lymphoprep (Axis-Shield, Oslo, Norway). Contaminating erythrocytes were lysed with ice-cold ammonium chloride buffer. Cells were washed with cold Hanks' balanced salt solution (HBSS) without Ca\(^{2+}\)/Mg\(^{2+}\) (HBSS\(^{-/-}\)) and resuspended in cold HBSS with Ca\(^{2+}\)/Mg\(^{2+}\) (HBSS\(^{+/+}\); both from Invitrogen, Breda, Netherlands).

Measurement of respiratory burst by oxidation of DHR to Rhodamine

The generation of reactive oxygen radicals by neutrophils was determined by measuring the oxidation of the nonfluorescent DHR to the green fluorescence rhodamine as described previously.\(^{37}\) Freshly isolated healthy donor neutrophils (final concentration 2.5 x 10\(^{6}\)/ml) were gradually warmed to 37°C and incubated with 5 μg/ml cytochalasin B (Sigma-Aldrich, Zwijndrecht, Netherlands) for 5 min at 37°C to enhance oxygen radical production. Then cells were loaded with 0.05 mM DHR (D632; Molecular Probes, Eugene, OR) for 10 min at 37°C. Sodium azide (2 mM) was added to prevent intracellular breakdown of H\(_2\)O\(_2\) by catalase. Then cells were primed with 2 ng/ml recombinant human TNF-α (rHuTNF-α; Boeringher Ingelheim, Heidelberg, Germany) for 15 min at 37°C and finally incubated with IgG fractions (final concentration 200 μg/ml) as stimulus. After 1 hour at 37°C, samples were washed with ice-cold HBSS\(^{-/-}\) supplemented with 1% BSA, pelleted, resuspended in HBSS\(^{+/+}\), and immediately analyzed by FACS analysis using a BD FACSCalibur flow cytometer. Neutrophils were identified by forward- and side-scatter properties, and the cellular rhodamine fluorescence intensity of 10,000 neutrophils was measured for each sample using a FITC argon laser with the excitation source at 488 nm. Results are expressed as mean fluorescence intensity (MFI) and were corrected for nonprimed neutrophils.

Degranulation assays

Freshly isolated healthy donor neutrophils (final concentration 1 x 10\(^{6}\)/ml) were gradually warmed to 37°C and treated with 5 μg/ml cytochalasin B (Sigma-Aldrich) for 5 min at 37°C. Then neutrophils were primed with 2 ng/ml rHuTNF-α (Boeringher Ingelheim) for 15 min at 37°C. The primed neutrophils (0.2 x 10\(^{6}\) cells/well) were incubated in a 96-well round-bottom microtiter plate (Greiner) with the IgG fractions (final concentration 200 μg/ml) for 120 min at 37°C. At the end of this incubation period, cell-free supernatants were collected for the determination of lactoferrin and elastase.

The lactoferrin content of the supernatant was measured as described previously.\(^{38}\) Briefly, Costar plates (Uden, The Netherlands) were coated with a F(ab')\(_2\) rabbit anti-human lactoferrin polyclonal antibody (667 ng/ml; Jackson ImmunoResearch Laboratories, West Grove, PA) overnight at room temperature, then washed and incubated with serial (two-fold) dilutions of the samples, starting at a dilution of 1:25, for 1 hour at 37°C. After washing, a rabbit anti-human lactoferrin polyclonal antibody conjugated with horseradish peroxidase (400 ng/ml; Jackson) was incubated for 30 min
at 37°C. Finally, TMB (3,3',5,5'-tetramethylbenzidine; Sigma-Aldrich) substrate was incubated for 15 min. The color reaction was stopped with 2N H2SO4. OD values were measured at 450 nm. The range of the lactoferrin standard (HK329; Hbt, Uden, Netherlands) was 0.16 to 100.00 ng/ml.

The elastase content of the supernatant was measured using a commercially available ELISA kit (HK319; Hbt), according to the manufacturer’s description. The range of the elastase standard was 0.39 to 25.00 ng/ml.

**Mice**

Mpo−/− mice were backcrossed to a C57BL/6 background seven times and bred in house. Female C57BL/6 wild-type mice were purchased from Harlan (Horst, Netherlands). All animal experiments were performed according to national guidelines and were approved by the local Animal Care and Experimentation Committee.

**Production of polyclonal mouse anti-MPO IgG**

Murine MPO was purified from WEHI-3 cells and used for immunization of Mpo−/− mice as described previously. Total IgG was isolated from pooled sera of immunized Mpo−/− mice, and the anti-MPO titer was analyzed by ELISA as reported previously.

**Induction and evaluation of anti-MPO IgG-induced NCGN**

Wildtype C57BL/6 mice (8 to 10 weeks, bodyweight 16 to 18 g) received 1 mg of anti-MPO IgG intravenously, followed by an intraperitoneal injection of 150 EU/g LPS (Escherichia Coli, serotype O26:B6; Sigma-Aldrich) 1 hour later. Mice were killed after 1 or 7 days, and kidneys were harvested, cut, and partly snap-frozen for immunohistochemistry and partly embedded in paraffin for histopathological evaluation. Plasma and (18-hour) urine were collected at both time points. Plasma samples were tested for circulating MPO antibody titers by ELISA as described previously. Urine samples were tested for hematuria (0 to 4+ score) and leukocyturia (0 to 3+ score) by Combur-Test strips (Roche Diagnostics BV, Almere, Netherlands) and albuminuria by ELISA (Bethyl Laboratories, Montgomery, TX). Periodic acid-Schiff staining was performed on paraffin sections, and the number of glomerular crescents was counted in 100 consecutive glomerular cross-sections in a blinded manner, as described previously. Immunohistochemical staining for neutrophils was performed on acetone-fixed 5-μm cryosections using an anti-rabbit peroxidase-based Envision+ system (DakoCytomation, Carpinteria, CA) according to the manufacturer’s protocol. Sections were incubated for 30 min with 10 μg/ml rat anti-mouse-Ly6G (clone 1A8; BD Biosciences, Breda, Netherlands) or isotype control antibody (IgG2a; Antigenix America, Huntington Station, NY) followed by a 30-minute incubation with 10 μg/ml unlabeled rabbit anti-rat secondary antibody (Vector Laboratories, Burlingame, CA). After detection of peroxidase activity with 3-amino-9-ethylcarbazole, sections were counterstained with Mayer’s hematoxylin.
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In vivo EndoS treatment

First, the effect of EndoS pretreatment of anti-MPO IgG was investigated. Mice were administered an intravenous injection of anti-MPO IgG that was pre-incubated (2 hours at 37°C) with GST-EndoS or GST (1 μg/100 μg IgG) to achieve deglycosylation. Mice were killed after 1 or 7 days ($n = 6$ per group) to evaluate disease development.

Then the effect of EndoS treatment at two different timepoints (3 hours [early] and 24 hours [late]) after disease induction was investigated. For this purpose, mice were administered an intravenous injection of 20 μg GST-EndoS or GST in 200 μl of PBS 3 or 24 hours after disease induction and killed on day 7 ($n = 6$ per group).

Statistical analysis

Data are expressed as mean ± SD and were analyzed using the unpaired two-tailed t-test. All statistical analyses were performed using SPSS 16.0 (SPSS Inc., Chicago, IL) or GraphPad Prism 5.00 for Windows (Graphpad Software, San Diego, CA). $P \leq 0.05$ was considered statistically significant.

RESULTS

EndoS-mediated glycan hydrolysis inhibits ANCA IgG-induced neutrophil activation

EndoS treatment efficiently hydrolyzes ANCA IgG glycans

MPO- and Pr3-ANCA IgG isolated from ANCA-positive patients with active, biopsy-proven NCGN (Table 1) were treated with glutathione S-transferase (GST)-tagged EndoS or GST alone. Subsequent SDS-PAGE analysis showed that EndoS treatment reduced the molecular weight of the IgG heavy chain by approximately 3 kD (Figure 1), which corresponds to loss of the Fc glycans. $^{15}$ *Lens culinaris* agglutinin lectin (LCA) blot analysis of the same samples showed that LCA could not bind to EndoS-treated ANCA IgG. It was previously shown by mass spectroscopy that the lack of LCA signal corresponds well with complete IgG glycan hydrolysis. $^{19}$ For some patients, the LCA signal was very low (patient 8) or not detectable (patients 7 and 9) in untreated ANCA IgG. Nevertheless, the combined analysis of lectin blots and stained SDS-PAGE clearly demonstrates that EndoS completely deglycosylates the heavy chains of all patients’ ANCA IgG.

EndoS treatment of ANCA IgG does not affect antigen-binding capacity

To verify that EndoS treatment does not affect the antigen-binding capacity of ANCA IgG, we tested the samples in a direct anti-MPO or anti-Pr3 ELISA (Figure 2, C and F). Deglycosylated ANCA IgG showed similar dilution curves compared with unmodified ANCA IgG. Also, the perinuclear staining pattern of MPO-ANCA IgG and the cytoplasmic staining pattern of Pr3-ANCA IgG on ethanol-fixed neutrophils were not affected by EndoS treatment (Figure 2, A, B, D and E). Together, these data indicate that glycan hydrolysis by EndoS does not affect the antigen-binding capacity of ANCA IgG.
EndoS in ANCA-mediated glomerulonephritis

Figure 2 EndoS-treated ANCA IgG retains antigen-binding capacity. (A, B, D, and E) Using indirect immunofluorescence on ethanol-fixed neutrophils, both deglycosylated (A) and unmodified (B) MPO-ANCA IgG show a perinuclear staining pattern, whereas deglycosylated (D) and unmodified (E) Pr3-ANCA IgG show a cytoplasmic staining pattern. (C and F) Deglycosylated (o) or unmodified (⎕) MPO- and Pr3-ANCA IgG samples are serially diluted and tested in a direct ELISA for anti-MPO or anti-Pr3, demonstrating similar titration curves. Representative examples of a MPO-ANCA IgG (C) and Pr3-ANCA IgG (F) are shown. Magnification, 400x. (color image on page 184)
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Figure 3 EndoS treatment inhibits ANCA-induced neutrophil respiratory burst. (A and B) Examples of a MPO- (A) and Pr3-ANCA IgG-induced (B) respiratory burst in TNF-α-primed neutrophils as measured by the dihydrorhodamine assay. The figure shows neutrophil oxygen radical production in untreated cells (gray) and cells stimulated with deglycosylated (solid line) or unmodified (dotted line) ANCA IgG. (C through F) Summary of the effect of EndoS-mediated deglycosylation of ANCA IgG on MPO-ANCA-induced (n = 5; C and D) and Pr3-ANCA-induced (n = 5; E and F) neutrophil oxygen radical production as determined on neutrophils from two donors and expressed as change in mean fluorescence intensity (donor 1 in C and E, donor 2 in D and F). Bars represent means ± SD. *P < 0.05; **P < 0.01.

Figure 4 EndoS treatment inhibits ANCA-induced neutrophil degranulation. (A and B) Effect of EndoS-mediated deglycosylation of MPO-ANCA IgG (black bars; n = 5) and Pr3-ANCA IgG (white bars; n = 5) on ANCA IgG-induced lactoferrin release as determined on neutrophils from two donors (donor 1 in A, donor 2 in B). (C and D) Effect of EndoS-mediated deglycosylation of MPO-ANCA IgG (black bars; n = 5) and Pr3-ANCA IgG (white bars; n = 5) on ANCA IgG-induced elastase release as determined on neutrophils from two donors (donor 1 in C, donor 2 in D). Bars represent means ± SD. *P < 0.05; **P < 0.01.
EndoS treatment inhibits ANCA IgG-induced neutrophil respiratory burst

Next, we tested the ability of ANCA IgG samples to activate TNF-α-primed neutrophils, using the dihydrorhodamine (DHR) respiratory burst assay. Consistent with previous studies, oxidative burst was detected only when neutrophils were primed with TNF-α (data not shown). IgG from healthy control subjects and patients with anti-glomerular basement membrane disease did not activate TNF-α-primed neutrophils (data not shown). In contrast, all Pr3- and MPO-ANCA IgGs were able to activate TNF-α-primed neutrophils, although to a variable extent (range in change in mean fluorescence intensity was 57 to 1091 in one neutrophil donor). ANCA-mediated induction of the oxidative burst was Fc tail dependent because ANCA-derived F(ab')2 fragments were not able to induce oxidative burst (Supplemental Figure 1, A and B). EndoS-mediated deglycosylation of MPO- and Pr3-ANCA IgG markedly attenuated ANCA-induced respiratory burst (Figure 3), demonstrating that IgG glycan hydrolysis by EndoS strongly attenuates the neutrophil-activating capacity of ANCA IgG.

EndoS treatment inhibits ANCA IgG-induced neutrophil degranulation

In addition to respiratory burst induction, we investigated whether deglycosylation of IgG by EndoS attenuates ANCA IgG-induced neutrophil degranulation. Both MPO- and Pr3-ANCA IgG were able to induce release of lactoferrin and elastase (Figure 4). F(ab')2 fragments from patient-derived

Figure 5  EndoS-mediated hydrolysis of the glycan moiety of murine anti-MPO IgG does not affect anti-MPO IgG titers after induction of crescentic glomerulonephritis. (A, top) A Coomassie Brilliant Blue staining is shown of murine anti-MPO IgG that was untreated (C), EndoS-treated (E), or GST control-treated (G). (A, bottom) LCA blot is shown from the same samples. (B) Co-administration of anti-MPO IgG and LPS to mice induces NCGN. Mice that received deglycosylated anti-MPO IgG (▲) had similar titers of anti-MPO antibodies compared with mice that received unmodified anti-MPO IgG (●) on day 1. On day 7, anti-MPO titers in both groups (unmodified anti-MPO IgG (▼) and deglycosylated anti-MPO IgG (♦)) are decreased compared with day 1. Data are means ± SD of 12 (day 1) or six (day 7) mice.
ANCA IgG were not able to induce lactoferrin and elastase release from TNF-α-primed neutrophils (Supplemental Figure 1, C and D). Deglycosylation of MPO- and Pr3-ANCA IgGs significantly reduced lactoferrin and elastase release in two neutrophil donors (Figure 4). These results demonstrate that IgG glycan hydrolysis by EndoS attenuates ANCA IgG-induced neutrophil degranulation.

Deglycosylation of anti-MPO IgG markedly diminishes induction of crescentic glomerulonephritis in mice

Next, we investigated whether deglycosylated anti-MPO IgG was able to induce NCGN in mice. EndoS treatment of mouse anti-MPO IgG efficiently hydrolyzed the heavy chain glycans of the IgG, as was shown by a reduction in the molecular weight of the IgG heavy chain, and loss of LCA binding (Figure 5A). Mice that received deglycosylated anti-MPO IgG and LPS had similar levels of circulating anti-MPO antibodies compared with mice that received unmodified anti-MPO IgG and LPS after 1

Figure 6 EndoS-mediated deglycosylation of anti-MPO IgG inhibits induction of hematuria (A), leukocyturia (B), and albuminuria (C) induced by anti-MPO IgG and LPS. (A) Induction of NCGN by unmodified anti-MPO IgG caused marked hematuria after 1 and 7 days (○). Mice that received deglycosylated anti-MPO IgG (▼) had less hematuria after 1 day. (B) Induction of NCGN by unmodified anti-MPO IgG caused increased leukocyturia after 1 and 7 days (○). Mice that received deglycosylated anti-MPO IgG (▼) had mild leukocyturia on day 1, whereas no leukocyturia could be detected on day 7. (C) Albuminuria before (baseline) and at 1 and 7 days after anti-MPO IgG/LPS administration. Mice that received unmodified anti-MPO IgG had increased urinary albumin concentrations on day 1 and even more on day 7. Mice that received deglycosylated anti-MPO IgG had urinary albumin levels that were comparable to baseline levels on days 1 and 7. White bars, unmodified anti-MPO IgG; black bars, deglycosylated anti-MPO IgG. Bars represent means ± SD. **P < 0.01; ***P < 0.001.
and 7 days (Figure 5B). Mice that received unmodified anti-MPO IgG developed marked hematuria and leukocyturia that lasted from day 1 until being killed on day 7 (Figure 6, A and B). On day 1, hematuria in these mice reached the maximum value of 4+, whereas leukocyturia was highest on day 7. In contrast, mice that received deglycosylated anti-MPO IgG displayed less hematuria on day 1, whereas leukocyturia on day 7 was completely absent. Albuminuria was increased on day 1 and even more on day 7 in mice that received unmodified anti-MPO IgG as compared with baseline levels. In contrast, in mice that were administered an injection of deglycosylated anti-

Figure 7 EndoS-mediated deglycosylation of anti-MPO IgG reduces early glomerular neutrophil influx. (A and B) Hematoxylin staining (A) and neutrophil staining (B) of a glomerulus on day 1 after disease induction from a mouse that received unmodified anti-MPO IgG and LPS demonstrate marked segmental infiltration of neutrophils. (C and D) Hematoxylin staining (C) and neutrophil staining (D) of a glomerulus on day 1 after disease induction from a mouse that received deglycosylated anti-MPO IgG and LPS demonstrate strongly reduced neutrophil infiltration. (E) Quantification of glomerular neutrophil influx on day 1 after disease induction in mice that received unmodified or deglycosylated anti-MPO IgG. Gcs, glomerular cross-section. ***P < 0.001. Magnification, 400x. (color image on page 185)
MPO IgG, albuminuria was comparable to baseline levels on days 1 and 7 (Figure 6C). These results demonstrate that EndoS-mediated deglycosylation of anti-MPO IgG markedly reduces urinary abnormalities in anti-MPO IgG/LPS-induced NCGN.

Analysis of glomerular neutrophil accumulation 1 day after induction of NCGN revealed a marked reduction in glomerular neutrophil influx in mice that received deglycosylated anti-MPO IgG compared with mice that received unmodified anti-MPO IgG (Figure 7). All mice that had received unmodified anti-MPO IgG developed a focal and segmental crescentic glomerulonephritis on day 7 (19.8 ± 4.8% glomerular crescents; Figure 8). In contrast, glomerular crescent formation was completely absent in five of six mice that had received deglycosylated anti-MPO IgG, whereas the other mouse had only 3% crescentic glomeruli. These results demonstrate that EndoS-mediated deglycosylation of anti-MPO IgG markedly diminishes early glomerular neutrophil influx and almost completely prevents glomerular crescent formation in anti-MPO IgG/LPS-induced NCGN.

Figure 8 EndoS-mediated deglycosylation of anti-MPO IgG prevents development of NCGN induced by anti-MPO IgG and LPS. (A) Overview of renal cortical tissue from a mouse administered an injection of unmodified anti-MPO IgG and LPS 7 days after disease induction, representing the focal and segmental nature of the glomerulonephritis. Glomerular crescents are indicated by arrows. (B) Overview of renal cortical tissue from a mouse administered an injection of deglycosylated anti-MPO IgG and LPS 7 days after disease induction, displaying normal renal morphology. (C) Detail of a glomerulus with a large cellular crescent on day 7, from a mouse that had received unmodified anti-MPO IgG and LPS. (D) Quantification of glomerular crescent formation in mice that received unmodified or deglycosylated anti-MPO IgG expressed as the percentage of glomerular crescents. Horizontal lines represent mean percentages in each group. ***P < 0.001. (A through C) Periodic acid-Schiff stain. Magnifications, 200x in A and B; 400x in C. (color image on page 185)
Figure 9 EndoS treatment does not affect anti-MPO IgG titers. (A) After induction of NCGN by anti-MPO IgG and LPS, mice were systemically treated with EndoS or GST (as a control) after 3 hours. Mice of both groups (EndoS [▲] and GST control [⎕]) had developed similar titers of anti-MPO IgG on day 1. In both groups (EndoS [♦] and GST control [▼]) anti-MPO titers decreased on day 7. Data are means ± SD of six mice. (B) After induction of NCGN by anti-MPO IgG and LPS, all mice had developed similar titers of circulating anti-MPO after 24 hours (■). Mice were treated with EndoS or GST (as a control) after 24 hours. In both groups (EndoS [♦] and GST control [▼]), anti-MPO titers decreased on day 7. Data are means ± SD of 12 (day 1) or six (day 7) mice.

Figure 10 Early (3 hours) but not late (24 hours) EndoS treatment reduces albuminuria in anti-MPO IgG/ LPS-induced NCGN. (A, B, and C) Early (3 hours) EndoS treatment. For hematuria (A) and leukocyturia (B), no differences are observed between GST-treated mice (⎕) and EndoS-treated mice (▼) after 1 and 7 days. (C) Albuminuria was significantly reduced in the EndoS-treated mice (black bars) on days 1 and 7 compared with GST-treated mice (white bars). Bars represent means ± SD. (D, E, and F) Late (24 hours) EndoS treatment. For hematuria (D) and leukocyturia (E), no differences are observed between GST-treated mice (⎕) and EndoS-treated mice (▼) after 7 days. Also for albuminuria (F), no differences are observed between GST-treated mice (black bars) and EndoS-treated mice (white bars) after 7 days. Bars represent means ± SD. *P < 0.05; **P < 0.01; ***P < 0.001.
Early (3 hours) but not late (24 hours) EndoS treatment attenuates anti-MPO IgG-induced NCGN

After demonstrating that EndoS-mediated deglycosylation of anti-MPO IgG largely prevents the induction of anti-MPO IgG-induced NCGN, we next investigated whether EndoS is beneficial when administered systemically. Mice were treated with EndoS either early (3 hours) or late (24 hours) after disease induction. Consistent with previous studies,17 EndoS treatment 3 hours after disease induction resulted in an efficient deglycosylation of serum IgG 24 hours after NCGN induction, whereas on day 7, LCA-positive IgG had reappeared (Supplemental Figure 2). Systemic EndoS treatment did not affect anti-MPO antibody titers (Figure 9). Early or late EndoS treatment had no significant effect on hematuria and leukocyturia (Figure 10, A through D). EndoS treatment 3 hours after disease induction reduced albuminuria on days 1 and 7 compared with control mice (Figure 10E); however, EndoS treatment 24 hours after disease induction did not affect albuminuria.

Figure 11 Early (3 hours) but not late (24 hours) EndoS treatment reduces glomerular crescent formation in anti-MPO IgG/LPS-induced NCGN. (A and B) Quantification of glomerular crescent formation in GST- and EndoS-treated mice expressed as the percentage of glomerular crescents. Early (3 hours; A) but not late (24 hours; B) EndoS treatment reduces the amount of glomerular crescents on day 7. Horizontal lines represent mean percentages in each group. ***P < 0.001 (C) Overview of renal cortical tissue 7 days after disease induction from a mouse that received early (3 hours) GST control treatment, representing the focal and segmental nature of the glomerulonephritis. Glomerular crescents are indicated by arrows. (D) Overview of renal cortical tissue 7 days after disease induction from a mouse that received early (3 hours) EndoS treatment; only a few glomerular crescents are seen. (C and D) Periodic acid-Schiff stain. Magnification, 100x in C and D. (color image on page 186)
EndoS in ANCA-mediated glomerulonephritis

(Figure 10F). Similarly, early EndoS treatment significantly reduced the percentage of glomerular crescents compared with control mice (Figure 11, A, C and D), whereas late EndoS treatment did not affect glomerular crescent formation (Figure 11B). Together, these results demonstrate that early (3 hours) but not late (24 hours) systemic EndoS administration rescues mice from disease progression.

DISCUSSION

In this study, we demonstrate that EndoS efficiently hydrolyzed the Fc glycans of patient ANCA IgG, thereby disrupting the neutrophil-activating capacity of ANCA in vitro. EndoS-mediated deglycosylation of mouse anti-MPO IgG almost completely prevented experimental anti-MPO IgG/LPS-mediated glomerulonephritis. Moreover, systemic EndoS administration 3 hours after disease induction rescued mice from disease progression, whereas disease development was not attenuated by EndoS treatment after 24 hours.

According to the widely accepted theory on the pathogenesis of ANCA-mediated vasculitis, ANCA-induced activation of primed neutrophils is crucial for disease development. Activation of neutrophils leads to oxygen radical production and the release of lytic granule constituents that are injurious to endothelial cells. ANCA-induced neutrophil activation is considered to involve simultaneous engagement of the F(ab’)2 portion of ANCA with ANCA antigens and interaction of the Fc tail of ANCA with Fc receptors. Our in vitro observations revealed that ANCA-mediated neutrophil activation, in particular degranulation, was attenuated but not completely blocked after Fc glycan removal. This finding suggests that Fc receptor-independent pathways are involved in ANCA-induced neutrophil activation as well. Indeed, in some studies, ANCA F(ab’)2 fragments could activate neutrophils; however, in our hands, ANCA F(ab’)2 fragments did not induce a respiratory burst or degranulation, suggesting that the remaining neutrophil-activating capacity of ANCA was due to interactions with Fc receptors that were not affected by IgG glycan hydrolysis.

EndoS hydrolyzes the heavy chain glycans of all four human IgG subclasses (IgG1 through 4) and of three mouse IgG subclasses (IgG1, IgG2a, and IgG2b). Glycan modification of IgG can alter the relative binding to FcγRs. The family of FcγRs consists of activating and inhibiting receptors that, together, in the normal situation, generate a well-balanced immune response; however, not all FcγR interactions are equally affected by changes in heavy chain glycosylation. For instance, although EndoS-mediated hydrolysis of human IgG2 takes place, this does not impair binding to FcγRs. In fact, IgG2 treated with EndoS shows increased binding to FcγRIIb and FcγRIIa. Interestingly, similar effects have been observed for EndoS-mediated hydrolysis of mouse IgG. In contrast to IgG1 and IgG2b, EndoS treatment did not diminish IgG2a-mediated effector functions in the mouse model of IgG-induced thrombocytopenia. This phenomenon may also explain our findings that EndoS-mediated deglycosylation of patients’ ANCA IgG did not completely prevent neutrophil activation in vitro and that hematuria and crescent formation were not completely blocked after administration of deglycosylated anti-MPO IgG in vivo.

To establish further the beneficial effects of EndoS-mediated IgG deglycosylation, we used the
mouse model of anti-MPO IgG/LPS-induced glomerulonephritis. In this model, co-administration of murine anti-MPO antibodies and LPS induces an acute glomerular inflammation that progresses to NCGN within days. One day after disease induction, signs of acute inflammation are present, such as hematuria and glomerular neutrophil influx, whereas leukocyturia, albuminuria and glomerular crescents are important disease characteristics on day 7. Because the pathogenicity of anti-MPO antibodies in mice seems to be FcR dependent, we hypothesized that EndoS-mediated deglycosylation of the anti-MPO IgG Fc tail could reduce the pathogenic effects of the antibodies. Indeed, we found that EndoS-mediated deglycosylation of anti-MPO IgG markedly diminished both early and late disease characteristics of this model.

After these promising findings with deglycosylated anti-MPO IgG, we investigated whether in vivo EndoS treatment was able to rescue mice from disease progression. Systemic injection of EndoS 3 hours after disease induction efficiently hydrolyzed circulating IgG and rescued mice from disease progression; however, systemic injection of EndoS 24 hours after disease induction did not significantly attenuate disease development. A possible explanation for this observation is that 24 hours after disease induction, mechanisms downstream of the antibody-mediated effects have already been initiated. Previous studies in this disease model have demonstrated a crucial role for (alternative) complement pathway activation, most likely via C5a generation. C5a promotes recruitment of more neutrophils to the inflammatory site, leading to a vicious, self-enhancing process with production of pro-inflammatory cytokines and further activation of complement. When deglycosylated anti-MPO IgG was administered, the initial start of this process was blocked and glomerular neutrophil influx on day 1 was strongly diminished. Also, when EndoS was administered systemically 3 hours after disease induction, EndoS was able to interfere with this process. Apparently, after 24 hours, the process was activated to such an extent that EndoS could not interfere anymore. At that stage, EndoS treatment could block only the antibody-mediated activation of new neutrophils entering the site but would not affect the pro-inflammatory cytokines and complement components that had already been formed. The hypothesis that complement activation is important after 24 hours is supported by the finding that complement inhibition in the same model via intervention with a C5-inhibiting monoclonal antibody after 24 hours attenuates disease progression, illustrated by a decrease in urinary abnormalities and a strong reduction in glomerular crescent formation.

A limitation of the mouse model of anti-MPO IgG/LPS-induced NCGN is that disease is induced by the passive, one-time transfer of anti-MPO IgG, which results in a rapid, monophasic renal disease. This is clearly different from ANCA-associated glomerulonephritis in humans, whereby ongoing disease activity results in the progressive accumulation of new lesions. This may be a particular important limitation when evaluating the effect of EndoS treatment on established disease. It would therefore be interesting to evaluate how (pre)treatment with EndoS would affect the development of glomerulonephritis in the established rat model of anti-MPO NCGN. In this model, Wistar-Kyoto rats are immunized with human MPO, which leads to the generation of antibodies against human
MPO that cross-react with rat MPO. In this chronic and progressive model, pauci-immune crescentic glomerulonephritis is observed after 8 weeks.\textsuperscript{29,30} Because it is not known yet how EndoS affects rat IgG, the feasibility of such experiments would need more investigation.

In patients with certain inflammatory diseases (e.g., rheumatoid arthritis, systemic lupus erythematosus, Crohn’s disease), the IgG glycan composition is different from that of healthy control subjects. Holland \textit{et al.}\textsuperscript{31} showed that this also applies to patients with active ANCA-associated systemic vasculitis. ANCA IgG was shown to contain more agalactosylated IgG molecules (with glycans containing no galactose residues). The authors also showed that ANCA IgG from these patients were hypogalactosylated only in their Fc but not in their F(ab’)\textsubscript{2} part, indicating that there was no defect in the glycosylation or processing machinery.\textsuperscript{32} Also, in our patients’ ANCA IgG, we observed differences in glycosylation (Figure 1). For some patients, the LCA signal was very low (patient 8) or even absent (patients 7 and 9), indicating that these patients might have an altered glycosylation of their IgG. Another explanation could be that these patients have an altered conformation of their IgG that blocks LCA from binding; however, the combination of stain and LCA blot showed that EndoS had hydrolyzed the IgG heavy chain glycans in all patients. Moreover, these ANCA IgGs did not behave differently compared with other ANCA IgGs in neutrophil activation assays. Together, these findings fit our hypothesis that ANCA IgG glycan modifications influence disease development.

We envision the use of glycan modification by EndoS as an induction therapy in the treatment of ANCA-associated vasculitis. In patients who present with acute active disease, one injection of EndoS would inactivate ANCA within minutes and in that way minimize damage to vessel walls that are not yet affected. Because our results suggest that EndoS treatment cannot reverse endothelial injury at existing inflammatory sites, EndoS would need to be combined with prevailing therapies. Many questions still need to be answered, however. First, because EndoS is a bacterial enzyme, its safety for administration to humans needs to be examined thoroughly. Second, it must be confirmed that EndoS is specific for glycans on human IgG and does not affect glycans on other proteins. Finally, a potential concern is that EndoS does not discriminate between autoantibodies and naturally occurring, protective antibodies, thereby leading to a decreased immune defense. Whether such a compromise between a reduction in autoimmunity and a decreased immune defense is medically acceptable will largely depend on the severity and reversibility of disease resulting from the autoantibodies.

In conclusion, we demonstrate that ANCA IgG glycan hydrolysis by EndoS attenuated ANCA-induced neutrophil respiratory burst and degranulation \textit{in vitro}. EndoS-mediated deglycosylation of anti-MPO IgG almost completely protected mice from anti-MPO IgG/LPS-induced glomerulonephritis. Moreover, systemic EndoS administration early after disease induction rescued mice from disease progression. These results indicate that Fc glycans of ANCA IgG are extremely important for induction of ANCA-mediated glomerulonephritis. We suggest that EndoS treatment can potentially function as an efficient induction therapy and in that way supplement current therapeutic strategies for ANCA-associated vasculitis.
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SUPPLEMENTARY DATA
Supplementary data for this chapter is available online at http://www.jasn.org/.

REFERENCES


