

IgG Glycan Hydrolysis Attenuates ANCA-Mediated Glomerulonephritis

Mirjan M. van Timmeren,* Betty S. van der Veen,* Coen A. Stegeman,[†] Arjen H. Petersen,* Thomas Hellmark,[‡] Mattias Collin,[§] and Peter Heeringa*

Departments of *Pathology and Medical Biology and [†]Internal Medicine, University Medical Center Groningen and University of Groningen, Groningen, Netherlands; and Departments of [‡]Nephrology and [§]Clinical Sciences, Lund University, Lund, Sweden

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 endoglycosidase 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.

J Am Soc Nephrol 21: 1103–1114, 2010. doi: 10.1681/ASN.2009090984

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).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).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 relapses³; therefore, more effective and less toxic therapeutic approaches are needed.

Similar to autoantibodies in other autoimmune diseases, ANCA are considered to be pathogenic.⁴ The pathogenic effect of ANCA comprises activation of cytokine-primed neutrophils within the mi-

Received September 25, 2009. Accepted February 10, 2010.

Published online ahead of print. Publication date available at www.jasn.org.

M.M.v.T. and B.S.v.d.V. contributed equally to this work.

Correspondence: Dr. Peter Heeringa, University Medical Center Groningen, Hanzeplein 1, Department of Pathology and Medical Biology, Hanzeplein 1, 9713 GZ, Groningen, Netherlands. Phone: +31-50-361-0789; Fax: +31-50-361-9911; E-mail: p.heeringa@med.umcg.nl

Copyright © 2010 by the American Society of Nephrology

crovasculature through binding of ANCA IgG to surface-expressed antigens with their F(ab')₂ portions and ligating to constitutively expressed neutrophil Fcγ receptors (FcγR), FcγRIIa, and FcγRIIIb, with their Fc tail.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.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.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.⁹⁻¹²

To function properly, IgG molecules require glycosylation of a conserved asparagine residue (Asn297) in the CH₂ 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.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 *Streptococcus pyogenes*, specifically hydrolyzes the conserved asparagine-linked glycans on the IgG heavy chains.^{14,15} EndoS hydrolyzes all subclasses of human IgG and almost completely abolishes IgG binding to FcγRs and IgG-dependent complement activation.¹⁶ *In vivo*, administration of EndoS to mice causes complete hydrolysis of circulating IgG within hours that lasts for several days.¹⁷ Importantly, *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.¹⁵ Interestingly, pretreatment of pathogenic autoantibodies with EndoS abrogates disease development in mouse models of arthritis and immune thrombocytopenic purpura.^{15,18} Systemic injection of EndoS also rescues mice from already established immune thrombocytopenic purpura and inhibits pathology in lupus-prone mice.^{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 *in vitro*. Furthermore, we investigated whether EndoS (pre)treatment diminishes glomerulonephritis development in experimental anti-MPO antibody/LPS-induced NCGN.

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

Table 1. Characteristics of ANCA-positive patients and control subjects used for IgG isolation

Parameter	ANCA Specificity	ANCA Titer	Gender	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

GBM, glomerular basement membrane.

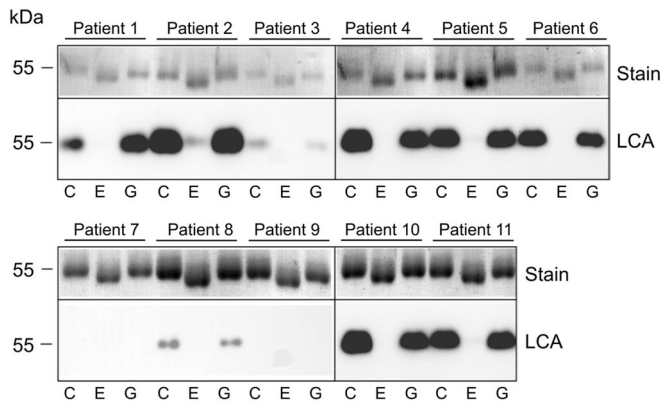


Figure 1. EndoS-mediated hydrolysis of the glycan moiety of ANCA IgG. Patient-derived MPO- and Pr3-ANCA IgG are treated with GST-tagged EndoS or GST alone. In the top part (Stain), a Coomassie Brilliant Blue staining is shown of MPO-ANCA IgG (patients 1 through 5) and Pr3-ANCA IgG (patients 6 through 11) that were untreated (C), EndoS-treated (E), or GST control-treated (G). In the bottom part (LCA), an LCA blot is shown from the same ANCA IgGs as presented in the top part. The binding site for LCA is located in the IgG heavy-chain glycan.

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 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,²⁰ 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 ANCA IgG were not able to induce lactoferrin and elastase release from TNF- α -primed neutrophils (Supplemental Figure 1, C and D). Deglyco-

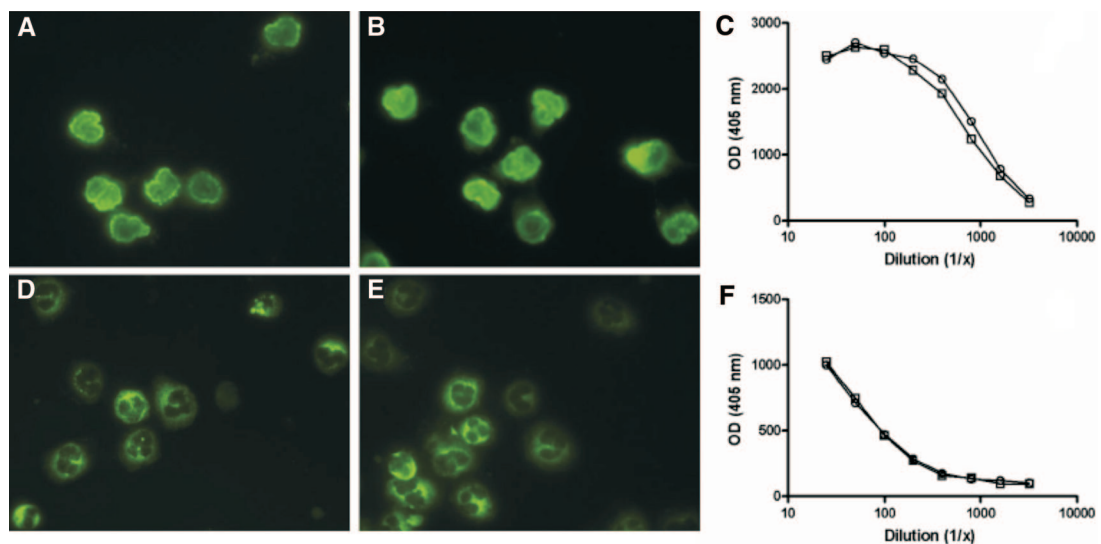


Figure 2. EndoS-treated ANCA IgG retains antigen-binding capacity. (A, B, D, and E) Using indirect immunofluorescence on ethanol-fixed neutrophils, both deglycosylated (A) and unmodified (B) MPO-ANCA IgG show a perinuclear staining pattern, whereas deglycosylated (D) and unmodified (E) Pr3-ANCA IgG show a cytoplasmic staining pattern. Deglycosylated (○) 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. (C and F) Representative examples of a MPO-ANCA IgG (C) and Pr3-ANCA IgG (F) are shown. Magnification, $\times 400$.

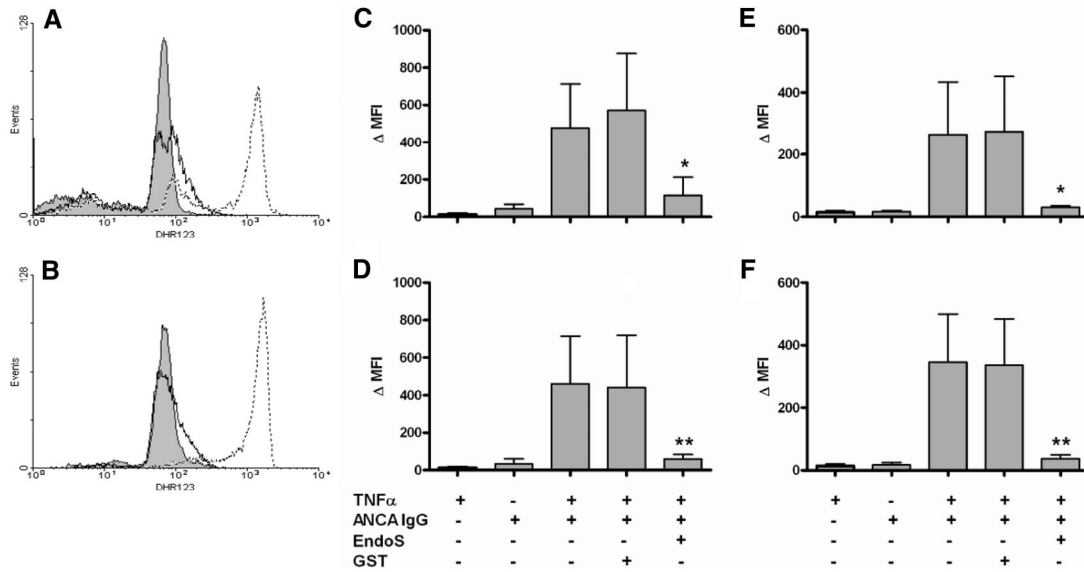


Figure 3. EndoS treatment inhibits ANCA-induced neutrophil respiratory burst. (A and B) Examples of a MPO- (A) and Pr3-ANCA IgG-induced (B) respiratory burst in TNF- α -primed neutrophils as measured by the dihydrorhodamine assay. The figure shows neutrophil oxygen radical production in untreated cells (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 \pm SD. * $P < 0.05$; ** $P < 0.01$.

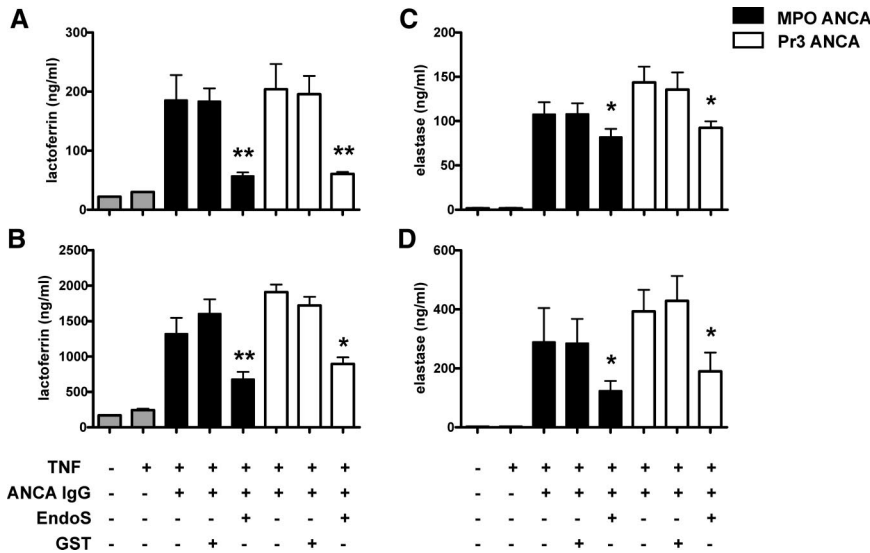


Figure 4. EndoS treatment inhibits ANCA-induced neutrophil degranulation. (A and B) Effect of EndoS-mediated deglycosylation of MPO-ANCA IgG (■; $n = 5$) and Pr3-ANCA IgG (□; $n = 5$) on ANCA IgG-induced lactoferrin release as determined on neutrophils from two donors (donor 1 in A, donor 2 in B). (C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

sylation 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 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

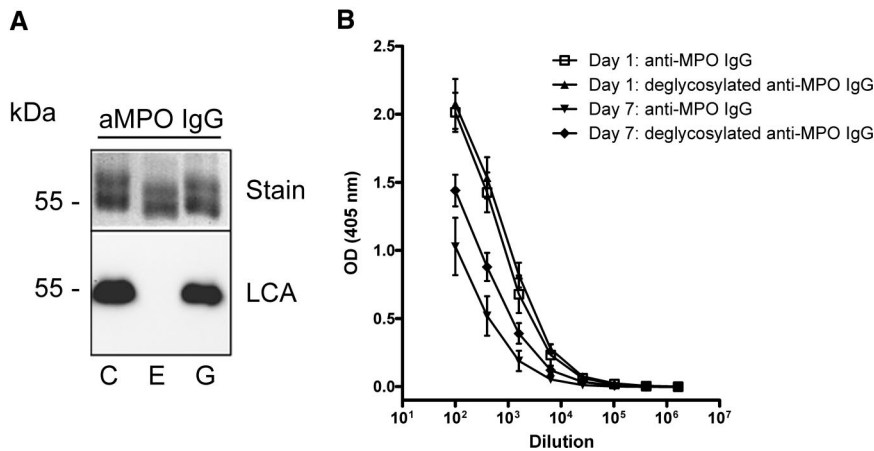


Figure 5. EndoS-mediated hydrolysis of the glycan moiety of murine anti-MPO IgG does not affect anti-MPO IgG titers after induction of crescentic glomerulonephritis. (A, top) A Coomassie Brilliant Blue staining is shown of murine anti-MPO IgG that was untreated (C), EndoS-treated (E), or GST control-treated (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 (\blacktriangle) had similar titers of anti-MPO antibodies compared with mice that received unmodified anti-MPO IgG (\square) on day 1. On day 7, anti-MPO titers in both groups (unmodified anti-MPO IgG [\blacktriangledown] and deglycosylated anti-MPO IgG [\blacklozenge]) are decreased compared with day 1. Data are means \pm SD of 12 (day 1) or six (day 7) mice.

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-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 ($19.8 \pm 4.8\%$ 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.

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 10F). Similarly, early EndoS treatment significantly reduced the percentage of glomerular crescents compared with control mice (Figure 11A, C, and D), whereas late EndoS treatment did not affect glomerular crescent formation (Figure 11B). Together, these results demon-

strate 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,⁵ 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.²¹ 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.^{6,7,22} 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^{21,23}; how-

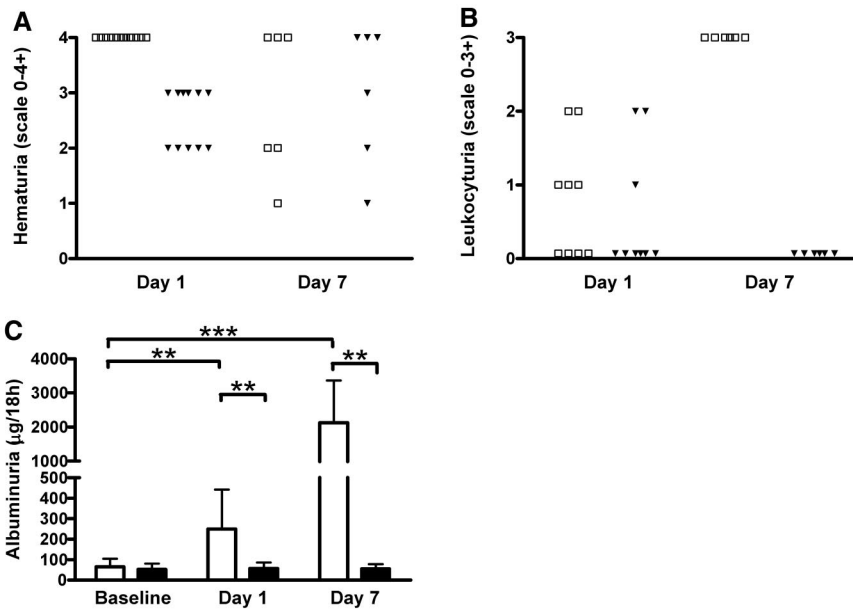


Figure 6. EndoS-mediated deglycosylation of anti-MPO IgG inhibits induction of hematuria (A), leukocyturia (B), and albuminuria (C) induced by anti-MPO IgG and LPS. (A) Induction of NCGN by unmodified anti-MPO IgG caused marked hematuria after 1 and 7 days (\square). Mice that received deglycosylated anti-MPO IgG (\blacktriangledown) had less hematuria after 1 day. (B) Induction of NCGN by unmodified anti-MPO IgG caused increased leukocyturia after 1 and 7 days (\square). Mice that received deglycosylated anti-MPO IgG (\blacktriangledown) 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. \square , Unmodified anti-MPO IgG; \blacksquare , deglycosylated anti-MPO IgG. Bars represent means \pm SD. $**P < 0.01$; $***P < 0.001$.

ever, 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).^{16,17} Glycan modification of IgG can alter the relative binding to Fc γ Rs. The family of Fc γ Rs consists of activating and inhibiting receptors that, together, in the normal situation, generate a well-balanced immune response²⁴; however, not all Fc γ R 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 Fc γ Rs. In fact, IgG2 treated with EndoS shows increased binding to Fc γ RIIb and Fc γ RIIa.¹⁶ 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.¹⁷ 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 7.⁹ Because the pathogenicity of anti-MPO antibodies in mice seems to be Fc γ R dependent,^{11,25} 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 demonstrated a crucial role for (alternative) complement pathway activation, most likely *via* C5a generation.¹² C5a promotes recruitment of more neutrophils to the inflammatory site, leading to a vicious, self-enhancing process with production of proinflammatory 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 proinflammatory cytokines and complement components that had

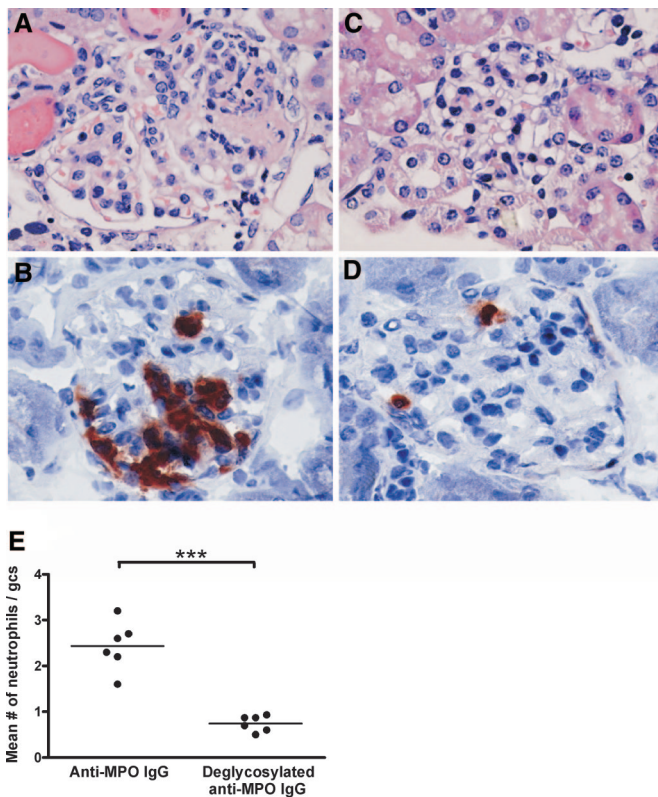


Figure 7. EndoS-mediated deglycosylation of anti-MPO IgG reduces early glomerular neutrophil influx. (A and B) Hematoxylin staining (A) and neutrophil staining (B) of a glomerulus on day 1 after disease induction from a mouse that received unmodified anti-MPO IgG and LPS demonstrate marked segmental 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, $\times 400$.

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 mAb after 24 hours attenuates disease progression, illustrated by a decrease in urinary abnormalities and a strong reduction in glomerular crescent formation.²⁶

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.^{27,28} This may be a particularly 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 develop-

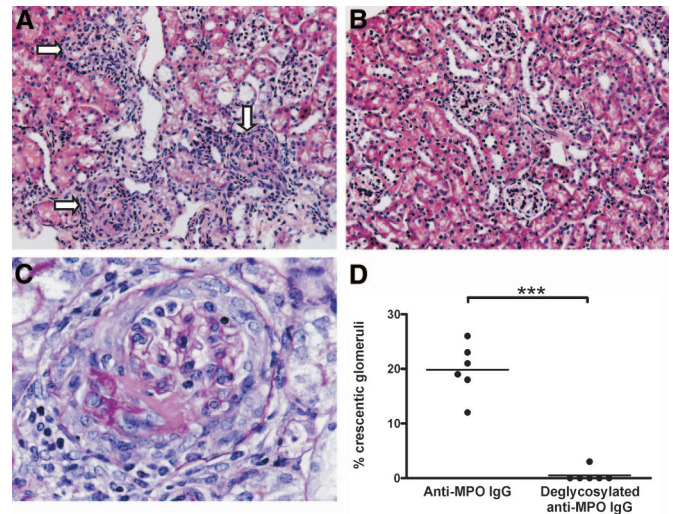


Figure 8. EndoS-mediated deglycosylation of anti-MPO IgG prevents development of NCGN induced by anti-MPO IgG and LPS. (A) Overview of renal cortical tissue from a mouse administered an injection of unmodified anti-MPO IgG and LPS 7 days after disease induction, representing the focal and segmental nature 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: $\times 200$ in A and B; $\times 400$ in C.

ment 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.^{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 *et al.*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')₂ part, indicating that there was no defect in the glycosylation or processing machinery.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 expla-

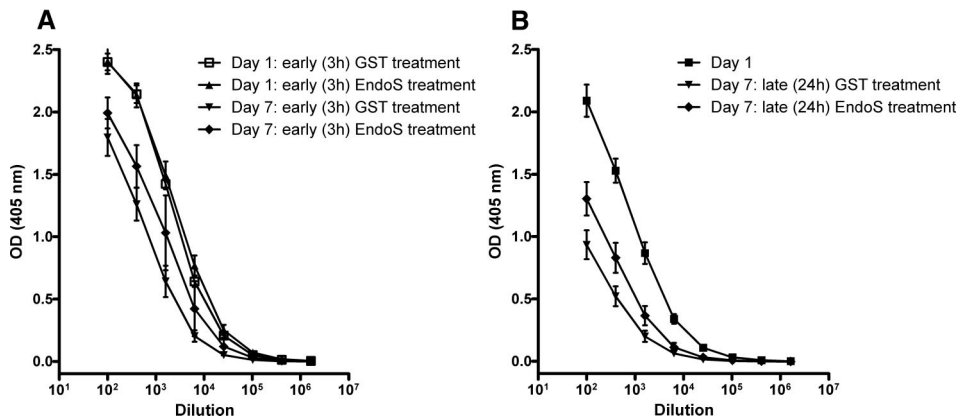


Figure 9. EndoS treatment does not affect anti-MPO IgG titers. (A) After induction of NCGN by anti-MPO IgG and LPS, mice were systemically treated with EndoS or GST (as a control) after 3 hours. Mice of both groups (EndoS [▲] and GST control [□]) had developed similar titers of anti-MPO IgG on day 1. In both groups (EndoS [◆] and GST control [▼]) anti-MPO titers decreased on day 7. Data are means \pm 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 mean \pm SD of 12 (day 1) or six (day 7) mice.

nation 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 *in vitro*. EndoS-mediated deglycosylation of anti-MPO IgG almost completely protected mice from anti-MPO IgG/LPS-induced glomerulonephritis. Moreover, sys-

temic 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.

CONCISE METHODS

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 tested for the presence of anti-Pr3 or anti-MPO antibodies by capture ELISA.^{33,34} Plasma samples were tested for ANCA titers by indirect immunofluorescence assay on ethanol-fixed neutrophils.^{34,35} 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 minutes at $14000 \times g$ 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.³⁶ 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 2 hours. The efficiency of GST-EndoS treatment was analyzed by SDS-PAGE and LCA blotting as described in 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 $\mu\text{g}/\text{ml}$ biotinylated LCA and 1 $\mu\text{g}/\text{ml}$ of streptavidin-horseradish peroxidase (Vector Laboratories, Burlingame, CA) and SuperSignal West Pico peroxidase substrate (Pierce, Rockford, IL). Membranes were analyzed using a

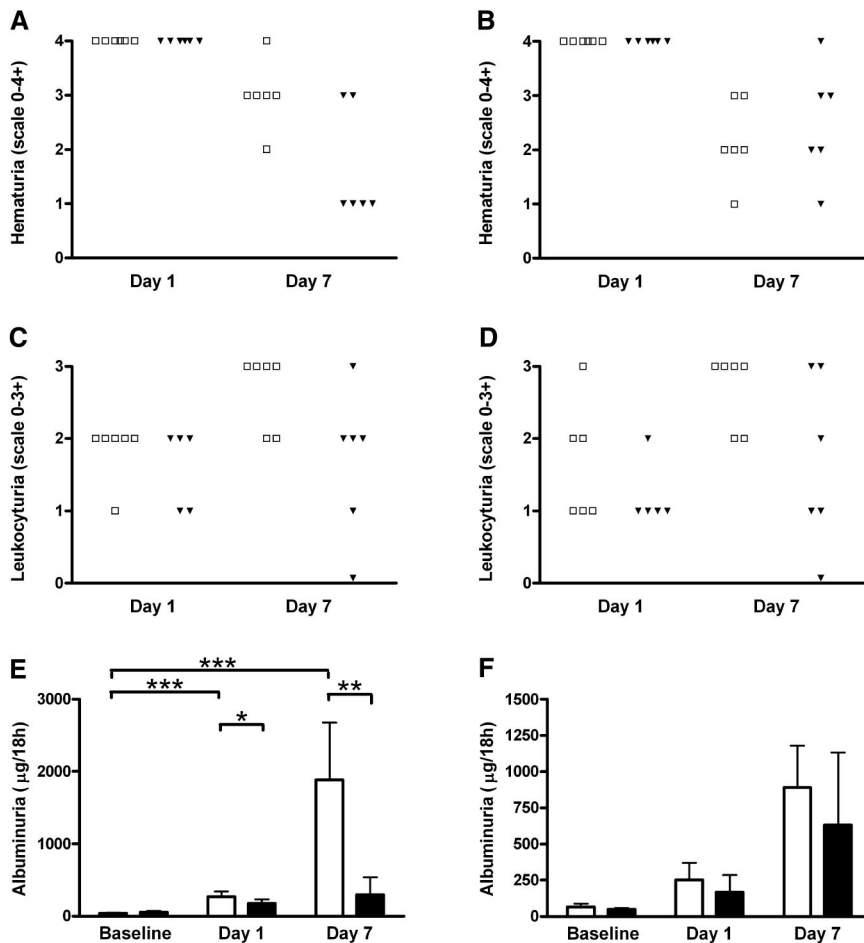


Figure 10. Early (3 hours) but not late (24 hours) EndoS treatment reduces albuminuria in anti-MPO IgG/LPS-induced NCGN. (A, C, and E) Early (3 hours) EndoS treatment. For hematuria (A) and leukocyturia (C), no differences are observed between GST-treated mice (□) and EndoS-treated mice (▼) after 1 and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

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.^{34,35}

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 μ g/ml MPO or 10 μ g/ml Pr3 (in the presence of 87 μ g/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 μ l 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 hours 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 control subjects 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 Ca²⁺/Mg²⁺ (HBSS^{-/-}) and resuspended in cold HBSS with Ca²⁺/Mg²⁺ (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 \times 10⁶/ml) were gradually warmed to 37°C and incubated with 5 μ g/ml cytochalasin B (Sigma-Aldrich, Zwijndrecht, Netherlands) for 5 minutes at 37°C to enhance oxygen radical production. Then cells were loaded with 0.05 mM DHR (D632; Molecular Probes, Eugene, OR) for 10 minutes at 37°C. Sodium azide (2 mM) was added to prevent intracellular breakdown of H₂O₂ by catalase. Then cells were primed with 2 ng/ml recombinant human TNF- α (rHuTNF α ; Boehringer Ingelheim, Heidelberg, Germany) for 15 minutes at 37°C and finally incubated with IgG fractions (final concentration 200 μ g/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.

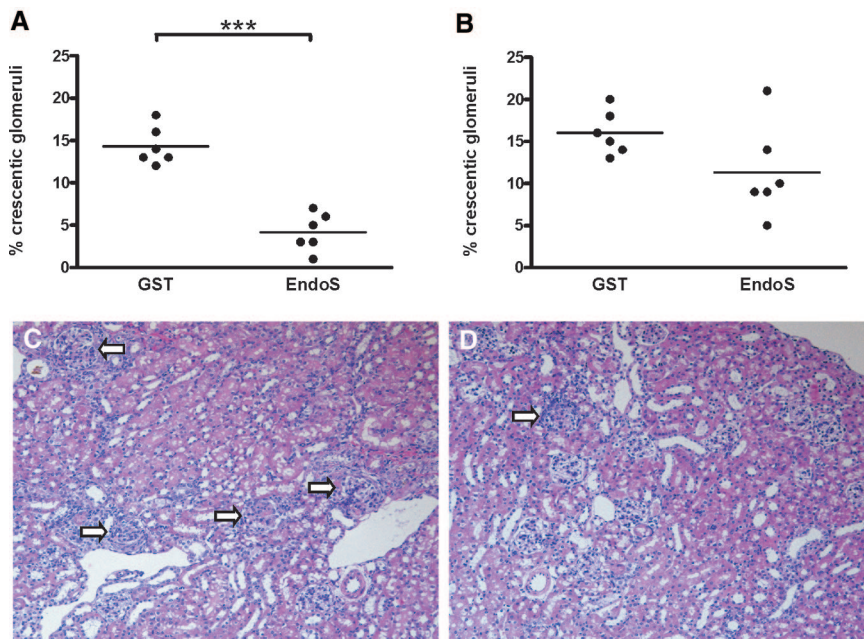


Figure 11. Early (3 hours) but not late (24 hours) EndoS treatment reduces glomerular crescent formation in anti-MPO IgG/LPS-induced NCGN. (A and B) Quantification of glomerular crescent formation in GST- and EndoS-treated mice expressed as the percentage of glomerular crescents. Early (3 hours; A) but 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, $\times 100$ in C and D.

Degranulation Assays

Freshly isolated healthy donor neutrophils (final concentration 1×10^6 /ml) were gradually warmed to 37°C and treated with $5 \mu\text{g}/\text{ml}$ cytochalasin B (Sigma-Aldrich) for 5 minutes at 37°C . Then neutrophils were primed with $2 \text{ ng}/\text{ml}$ rHuTNF α (Boehringer Ingelheim) for 15 minutes at 37°C . The primed neutrophils (0.2×10^6 cells/well) were incubated in a 96-well round-bottom microtiter plate (Greiner) with the IgG fractions (final concentration $200 \mu\text{g}/\text{ml}$) for 120 minutes 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, Netherlands) were coated with an F(ab')₂ rabbit anti-human lactoferrin polyclonal antibody ($667 \text{ ng}/\text{ml}$; 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 ($400 \text{ ng}/\text{ml}$; Jackson) was incubated for 30 minutes at 37°C . Finally, TMB (3,3',5,5'-tetramethylbenzidine; Sigma-Aldrich) substrate was incubated for 15 minutes. The color reaction was stopped with $2 \text{ N H}_2\text{SO}_4$. OD values were measured at 450 nm . The

range of the lactoferrin standard (HK329; Hbt, Uden, Netherlands) was 0.16 to $100.00 \text{ ng}/\text{ml}$.

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 $25.00 \text{ ng}/\text{ml}$.

Mice

Mpo^{-/-} mice were backcrossed to a C57BL/6 background seven times³⁹ 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.⁹ Total IgG was isolated from pooled sera of immunized *Mpo*^{-/-} mice, and the anti-MPO titer was analyzed by ELISA as reported previously.⁹

Induction and Evaluation of Anti-MPO IgG-Induced NCGN

Wild-type C57BL/6 mice (8 to 10 weeks, body weight 16 to 18 g) received 1 mg of anti-MPO IgG intravenously, followed by an intraperitoneal injection of $150 \text{ EU}/\text{g}$ 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 histopathologic 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.⁹ 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.²⁶ Immunohistochemical staining for neutrophils was performed on acetone-fixed $5\text{-}\mu\text{m}$ cryosections using an anti-rabbit peroxidase-based Envision+ system (DakoCytomation, Carpinteria, CA) according to the manufacturer's protocol. Sections were incubated for 30 minutes with $10 \mu\text{g}/\text{ml}$ 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 $10 \mu\text{g}/\text{ml}$ 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.

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 preincubated (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 time points (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 means \pm 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.

ACKNOWLEDGMENTS

This study was supported by grants from the Dutch Kidney Foundation (C07-2204 and C09-2314 to P.H. and M.M.v.T.); the Swedish Research Council (project 2005-4791 to M.C.); the Foundations of Crafoord (M.C.), Kock (M.C.), Zoégas (M.C.), Bergvall (M.C.), Österlund (M.C.), Groschinsky (M.C.), and Wiberg (M.C.); the Swedish Society for Medicine (M.C.); the Royal Physiografic Society (M.C.); King Gustaf V's Memorial Fund (M.C.); and Hansa Medical AB (M.C.). P.H. is supported by a grant from the Netherlands Organization for Scientific Research (NWO VIDI grant 917.66.341). M.C. is the recipient of an Assistant Professorship from the Swedish Research Council.

Part of this work was presented at the annual meeting of the American Society of Nephrology; October 27 through November 1, 2009; San Diego, CA.

We thank Martin Schipper, Henk Moorlag, and Ulla Johannesson for excellent technical assistance.

DISCLOSURES

Hansa Medical AB and Genovis AB have filed patent application on the *in vivo* and *in vitro* use of EndoS, respectively. M.C. is listed as an inventor, and the applications are pending. M.C. is a part-time scientific consultant for Hansa Medical AB. Active and inactive EndoS have recently been developed as biotechnological tools and made commercially available as IgGZero and Fc-Docker, respectively (<http://www.genovis.com>).

REFERENCES

1. Kallenberg CG, Heeringa P, Stegeman CA: Mechanisms of disease: Pathogenesis and treatment of ANCA-associated vasculitides. *Nat Clin Pract Rheumatol* 2: 661–670, 2006
2. Franssen CF, Stegeman CA, Kallenberg CG, Gans RO, De Jong PE, Hoorntje SJ, Tervaert JW: Antiproteinase 3- and antimyeloperoxidase-associated vasculitis. *Kidney Int* 57: 2195–2206, 2000
3. Turnbull J, Harper L: Adverse effects of therapy for ANCA-associated vasculitis. *Best Pract Res Clin Rheumatol* 23: 391–401, 2009
4. van Timmeren MM, Chen M, Heeringa P: Review article: Pathogenic role of complement activation in anti-neutrophil cytoplasmic autoantibody-associated vasculitis. *Nephrology (Carlton)* 14: 16–25, 2009
5. Heeringa P, Huugen D, Tervaert JW: Anti-neutrophil cytoplasmic autoantibodies and leukocyte-endothelial interactions: A sticky connection? *Trends Immunol* 26: 561–564, 2005
6. Mulder AH, Heeringa P, Brouwer E, Limburg PC, Kallenberg CG: Activation of granulocytes by anti-neutrophil cytoplasmic antibodies (ANCA): A Fc gamma RII-dependent process. *Clin Exp Immunol* 98: 270–278, 1994
7. Porges AJ, Redecha PB, Kimberly WT, Csernok E, Gross WL, Kimberly RP: Anti-neutrophil cytoplasmic antibodies engage and activate human neutrophils via Fc gamma RIIa. *J Immunol* 153: 1271–1280, 1994
8. Xiao H, Heeringa P, Hu P, Liu Z, Zhao M, Aratani Y, Maeda N, Falk RJ, Jennette JC: Antineutrophil cytoplasmic autoantibodies specific for myeloperoxidase cause glomerulonephritis and vasculitis in mice. *J Clin Invest* 110: 955–963, 2002
9. Huugen D, Xiao H, van Esch A, Falk RJ, Peutz-Kootstra CJ, Buurman WA, Tervaert JW, Jennette JC, Heeringa P: Aggravation of anti-myeloperoxidase antibody-induced glomerulonephritis by bacterial lipopolysaccharide: Role of tumor necrosis factor-alpha. *Am J Pathol* 167: 47–58, 2005
10. Xiao H, Heeringa P, Liu Z, Huugen D, Hu P, Maeda N, Falk RJ, Jennette JC: The role of neutrophils in the induction of glomerulonephritis by anti-myeloperoxidase antibodies. *Am J Pathol* 167: 39–45, 2005
11. Nolan SL, Kalia N, Nash GB, Kamel D, Heeringa P, Savage CO: Mechanisms of ANCA-mediated leukocyte-endothelial cell interactions *in vivo*. *J Am Soc Nephrol* 19: 973–984, 2008
12. Xiao H, Schreiber A, Heeringa P, Falk RJ, Jennette JC: Alternative complement pathway in the pathogenesis of disease mediated by anti-neutrophil cytoplasmic autoantibodies. *Am J Pathol* 170: 52–64, 2007
13. Raju TS: Terminal sugars of Fc glycans influence antibody effector functions of IgGs. *Curr Opin Immunol* 20: 471–478, 2008
14. Collin M, Olsen A: EndoS, a novel secreted protein from *Streptococcus pyogenes* with endoglycosidase activity on human IgG. *EMBO J* 20: 3046–3055, 2001
15. Collin M, Shannon O, Bjorck L: IgG glycan hydrolysis by a bacterial enzyme as a therapy against autoimmune conditions. *Proc Natl Acad Sci U S A* 105: 4265–4270, 2008
16. Allhorn M, Olin AI, Nimmerjahn F, Collin M: Human IgG/Fc gamma R interactions are modulated by streptococcal IgG glycan hydrolysis. *PLoS ONE* 3: e1413, 2008
17. Albert H, Collin M, Dudziak D, Ravetch JV, Nimmerjahn F: *In vivo* enzymatic modulation of IgG glycosylation inhibits autoimmune disease in an IgG subclass-dependent manner. *Proc Natl Acad Sci U S A* 105: 15005–15009, 2008
18. Nandakumar KS, Collin M, Olsen A, Nimmerjahn F, Blom AM, Ravetch JV, Holmdahl R: Endoglycosidase treatment abrogates IgG arthritogenicity: Importance of IgG glycosylation in arthritis. *Eur J Immunol* 37: 2973–2982, 2007
19. Collin M, Fischetti VA: A novel secreted endoglycosidase from *Enterococcus faecalis* with activity on human immunoglobulin G and ribonuclease B. *J Biol Chem* 279: 22558–22570, 2004
20. van Rossum AP, Rarok AA, Huitema MG, Fassina G, Limburg PC, Kallenberg CG: Constitutive membrane expression of proteinase 3 (PR3) and neutrophil activation by anti-PR3 antibodies. *J Leukoc Biol* 76: 1162–1170, 2004
21. Falk RJ, Terrell RS, Charles LA, Jennette JC: Anti-neutrophil cytoplasmic autoantibodies induce neutrophils to degranulate and produce

- oxygen radicals in vitro. *Proc Natl Acad Sci U S A* 87: 4115–4119, 1990
22. Kocher M, Edberg JC, Fleit HB, Kimberly RP: Antineutrophil cytoplasmic antibodies preferentially engage Fc gammaRIIb on human neutrophils. *J Immunol* 161: 6909–6914, 1998
 23. Kettritz R, Jennette JC, Falk RJ: Crosslinking of ANCA-antigens stimulates superoxide release by human neutrophils. *J Am Soc Nephrol* 8: 386–394, 1997
 24. Nimmerjahn F, Ravetch JV: Fc gamma receptors as regulators of immune responses. *Nat Rev Immunol* 8: 34–47, 2008
 25. Xiao H, Heeringa P, Schreiber A, Falk RJ, Jennette JC: The role of Fc gamma receptors in induction of glomerulonephritis and pulmonary granulomatous inflammation in mice by anti-myeloperoxidase antibodies (anti-MPO) [Abstract]. *J Am Soc Nephrol* 15: 37A, 2004
 26. Huugen D, van Esch A, Xiao H, Peutz-Kootstra CJ, Buurman WA, Tervaert JW, Jennette JC, Heeringa P: Inhibition of complement factor C5 protects against anti-myeloperoxidase antibody-mediated glomerulonephritis in mice. *Kidney Int* 71: 646–654, 2007
 27. Bajema IM, Hagen EC, Hermans J, Noel LH, Waldherr R, Ferrario F, van der Woude FJ, Bruijn JA: Kidney biopsy as a predictor for renal outcome in ANCA-associated necrotizing glomerulonephritis. *Kidney Int* 56: 1751–1758, 1999
 28. Neumann I, Kain R, Regele H, Soleiman A, Kandutsch S, Meisl FT: Histological and clinical predictors of early and late renal outcome in ANCA-associated vasculitis. *Nephrol Dial Transplant* 20: 96–104, 2005
 29. Little MA, Smyth CL, Yadav R, Ambrose L, Cook HT, Nourshargh S, Pusey CD: Antineutrophil cytoplasm antibodies directed against myeloperoxidase augment leukocyte-microvascular interactions in vivo. *Blood* 106: 2050–2058, 2005
 30. Little MA, Smyth L, Salama AD, Mukherjee S, Smith J, Haskard D, Nourshargh S, Cook HT, Pusey CD: Experimental autoimmune vasculitis: An animal model of anti-neutrophil cytoplasmic autoantibody-associated systemic vasculitis. *Am J Pathol* 174: 1212–1220, 2009
 31. Holland M, Takada K, Okumoto T, Takahashi N, Kato K, Adu D, Ben-Smith A, Harper L, Savage CO, Jefferis R: Hypogalactosylation of serum IgG in patients with ANCA-associated systemic vasculitis. *Clin Exp Immunol* 129: 183–190, 2002
 32. Holland M, Yagi H, Takahashi N, Kato K, Savage CO, Goodall DM, Jefferis R: Differential glycosylation of polyclonal IgG, IgG-Fc and IgG-Fab isolated from the sera of patients with ANCA-associated systemic vasculitis. *Biochim Biophys Acta* 1760: 669–677, 2006
 33. Tervaert JW, Goldschmeding R, Elema JD, van der Giessen M, Huitema MG, van der Hem GK, The TH, von dem Borne AE, Kallenberg CG: Autoantibodies against myeloid lysosomal enzymes in crescentic glomerulonephritis. *Kidney Int* 37: 799–806, 1990
 34. Tervaert JW, Mulder L, Stegeman CA, Elema J, Huitema M, The H, Kallenberg C: Occurrence of autoantibodies to human leucocyte elastase in Wegener's granulomatosis and other inflammatory disorders. *Ann Rheum Dis* 52: 115–120, 1993
 35. Brouwer E, Tervaert JW, Horst G, Huitema MG, van der Giessen M, Limburg PC, Kallenberg CG: Predominance of IgG1 and IgG4 subclasses of anti-neutrophil cytoplasmic autoantibodies (ANCA) in patients with Wegener's granulomatosis and clinically related disorders. *Clin Exp Immunol* 83: 379–386, 1991
 36. Collin M, Olsen A: Effect of SpeB and EndoS from *Streptococcus pyogenes* on human immunoglobulins. *Infect Immun* 69: 7187–7189, 2001
 37. Hu N, Westra J, Huitema MG, Bijl M, Brouwer E, Stegeman CA, Heeringa P, Limburg PC, Kallenberg CG: Coexpression of CD177 and membrane proteinase 3 on neutrophils in antineutrophil cytoplasmic autoantibody-associated systemic vasculitis: Anti-proteinase 3-mediated neutrophil activation is independent of the role of CD177-expressing neutrophils. *Arthritis Rheum* 60: 1548–1557, 2009
 38. Franssen CF, Huitema MG, Muller Kobold AC, Oost-Kort WW, Limburg PC, Tiebosch A, Stegeman CA, Kallenberg CG, Tervaert JW: *In vitro* neutrophil activation by antibodies to proteinase 3 and myeloperoxidase from patients with crescentic glomerulonephritis. *J Am Soc Nephrol* 10: 1506–1515, 1999
 39. Aratani Y, Koyama H, Nyui S, Suzuki K, Kura F, Maeda N: Severe impairment in early host defense against *Candida albicans* in mice deficient in myeloperoxidase. *Infect Immun* 67: 1828–1836, 1999

Supplemental information for this article is available online at <http://www.jasn.org/>.