A Distinct Macrophage Subset Mediating Tissue Destruction and Neovascularization in Giant Cell Arteritis: Implication of the YKL-40/Interleukin-13 Receptor α2 Axis

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INTRODUCTION

Giant cell arteritis (GCA) is an inflammatory disease that affects the medium- and large-sized arteries and has potential serious acute complications, such as blindness and stroke (1). Chronic complications can also occur, since long-term aortic inflammation is associated with the development of aneurysms and aorta dissections (2,3). GCA is commonly treated with glucocorticoids (GCs). More recently, tocilizumab (interleukin-6 [IL-6] receptor blockade) has become available as GC-sparing therapy in GCA (4). Both GCs and tocilizumab treatment suppress disease symptoms. It is less clear, however, if GCs and tocilizumab

Methods. Immunohistochemistry was performed on GCA temporal artery biopsy specimens (n = 12) and aortas (n = 10) for detection of YKL-40, its receptor interleukin-13 receptor α2 (IL-13Ra2), macrophage markers PU.1 and CD206, and the tissue--destructive protein matrix metalloproteinase 9 (MMP-9). Ten noninflamed temporal artery biopsy specimens served as controls. In vitro experiments with granulocyte–macrophage colony-stimulating factor (GM-CSF)– or macrophage colony-stimulating factor (M-CSF)–skewed monocyte-derived macrophages were conducted to study the dynamics of YKL-40 production. Next, small interfering RNA–mediated knockdown of YKL-40 in GM-CSF–skewed macrophages was performed to study its effect on MMP-9 production. Finally, the angiogenic potential of YKL-40 was investigated by tube formation experiments using human microvascular endothelial cells (HMVECs).

Results. YKL-40 was abundantly expressed by a CD206+MMP-9+ macrophage subset in inflamed temporal arteries and aortas. GM-CSF–skewed macrophages from GCA patients, but not healthy controls, released significantly higher levels of YKL-40 compared to M-CSF–skewed macrophages (P = 0.039). In inflamed temporal arteries, IL-13Ra2 was expressed by macrophages and endothelial cells. Functionally, knockdown of YKL-40 led to a 10–50% reduction in MMP-9 production by macrophages, whereas exposure of HMVECS to YKL-40 led to significantly increased tube formation.

Conclusion. In GCA, a GM-CSF–skewed, CD206+MMP-9+ macrophage subset expresses high levels of YKL-40 which may stimulate tissue destruction and angiogenesis through IL-13Ra2 signaling. Targeting YKL-40 or GM-CSF may inhibit macrophages that are currently insufficiently suppressed by glucocorticoids.
suppress smoldering vascular inflammation, which is likely associated with relapses and chronic complications of GCA (5–9).

The inflamed vessel wall in GCA patients is characterized by a granulomatous tissue reaction involving mainly T cells and macrophages (1). Besides promoting ongoing inflammation, macrophages release factors leading to myofibroblast proliferation (e.g., platelet-derived growth factor), angiogenesis (e.g., vascular endothelial growth factor [VEGF]), and tissue destruction (e.g., matrix metalloproteinase 9 [MMP-9]) (10,11). These processes are responsible for the pathologic changes associated with the serious complications of GCA, such as vascular occlusion due to intima hyperplasia and aneurysms due to media degradation. Importantly, several studies have shown that even with treatment, macrophage activity persists in GCA patients, indicating that currently available treatments do not sufficiently suppress the local inflammatory response (6,12). Therefore, new strategies and targets are needed to adequately halt inflammation and destruction of the vessel wall.

We recently described functionally heterogeneous macrophage subsets in GCA lesions, likely due to local signals involving granulocyte–macrophage colony-stimulating factor (GM-CSF) (13). We demonstrated the presence of a specific macrophage subset in and around the media layer that lacked folate receptor β expression but showed high expression of the mannose receptor CD206. Importantly, these CD206+ macrophages exclusively expressed MMP-9, indicating that these cells are likely to be important in media destruction. Moreover, others reported MMP-9 to be an important mediator of endothelial cell migration and neovascularization, thus facilitating T cell and macrophage recruitment to the vessel wall, processes crucial in the pathogenesis of GCA (11). Subsequent in vitro experiments demonstrated that the CD206+ macrophage phenotype can be induced by culturing macrophages with GM-CSF, a growth factor abundantly expressed in GCA lesions (13). Our findings on functional macrophage heterogeneity in GCA lesions, along with additional recent studies on GM-CSF signaling in GCA (12), prompted us to investigate the phenotype and functioning of the CD206+ macrophage subset in GCA in more detail. To this end, we took clues from the field of cancer immunology on tumor-associated macrophages.

Tumor-associated macrophages promote tumor growth and are associated with poor survival (14). Prior studies indicated an important role for YKL-40 (also known as chitinase 3-like protein 1) produced by tumor-associated macrophages in various inflammatory and tissue remodeling processes, including angiogenesis and tissue destruction. Furthermore, YKL-40 has been implicated as an upstream signal for MMP-9 production (15). Although early reports described elevated serum levels of YKL-40 in autoinflammatory conditions, including GCA (16), less is known about the role of YKL-40 in the immunopathology of GCA. YKL-40 is a chitinase-like protein, meaning that it is able to bind to chitin but does not cleave it, owing to the lack of enzymatic activity of YKL-40 (14). YKL-40 production by innate immune cells, including macrophages, is induced by various stimuli, including the cytokines IL-6, IL-1β, and interferon-γ (IFNγ) (17).

Interestingly, we previously showed that serum levels of YKL-40 are elevated in GCA patients at diagnosis, but do not normalize after GC treatment. In contrast, acute-phase markers such as C-reactive protein are strongly suppressed by treatment with GCs and tocilizumab, since their levels are highly dependent on IL-6 in GCA (7,18). Moreover, abundant expression of YKL-40 has been documented in GCA temporal artery biopsy specimens (7,16). However, it is yet unknown which specific cell type(s) produce YKL-40 and what the role of YKL-40 is in the immunopathogenesis of GCA.

IL-13 receptor α2 (IL-13Ra2), a high-affinity receptor for IL-13 that is distinct from IL-13Ra1, was previously thought to be a decoy receptor for IL-13 due to the lack of a signal transducing cytoplasmic tail (19,20). However, recent studies demonstrated the activation of MAPK, Akt, ERK, and STAT3 pathways with monocyte-derived macrophages upon binding of either IL-13 or YKL-40 to IL-13Ra2 (21–25). The expression of this receptor in the context of GCA has so far not been reported.

In this study, we aimed to determine the cellular source of YKL-40 and to investigate its contribution to vascular pathology in GCA. Using immunohistochemistry (IHC) and immunofluorescence, we identified the subset of CD206+ macrophages as the main cellular source of YKL-40 in inflamed temporal arteries and in the aorta. In the same tissues, we next examined the expression of IL-13Ra2 to establish whether YKL-40 can signal at the site of inflammation. To assess whether YKL-40 is an upstream modulator of the tissue-destructive MMP-9, we performed in vitro experiments with monocyte-derived macrophages on the dynamics of YKL-40 and MMP-9 expression. Finally, we confirmed the angiogenic potential of YKL-40 in vitro in a tube formation assay. Our data support an important role for the YKL-40/IL-13Ra2 axis in tissue destruction and neovascularization in GCA.

PATIENTS AND METHODS


Patients. Twelve inflamed temporal artery tissue samples from treatment-naive patients with histologically proven GCA were studied. The diagnosis of GCA was based on a pathologist’s assessment of the temporal artery biopsy sample as positive for panarteritis. Ten inflamed aorta tissue samples from patients with an untreated GCA-related aneurysm were also included (13). Ten noninflamed temporal artery biopsy specimens were included as controls. These noninflamed temporal artery biopsy specimens were obtained from patients with positron emission tomography (PET)-proven GCA (skip lesions; n = 3), patients with isolated polymyalgia rheumatica (PMR; n = 5), and individuals who had neither GCA nor
PMR (n = 2). The study was approved by the institutional review board of the University Medical Center Groningen (METc2010/222), and written informed consent was obtained. All procedures were conducted in compliance with the Declaration of Helsinki.

Serum and frozen peripheral blood mononuclear cells (PBMCs) from treatment-naïve GCA patients and age- and sex-matched healthy controls were used for Luminex assay and in vitro studies. (Baseline characteristics of the patients and controls are shown in Supplementary Table 1, available on the Arthritis & Rheumatology website at http://onlinelibrary.wiley.com/doi/10.1002/art.41887/abstract.) GCA diagnoses were confirmed by temporal artery biopsy and/or PET. Healthy controls were screened by health assessment questionnaires, physical examination, and laboratory tests for past and current morbidities and were excluded if they were not healthy. Follow-up serum samples were obtained from GCA patients 1 year after the start of treatment and at treatment-free remission for the Luminex analysis. Patients were considered to be in treatment-free remission if it had been ≥2 years since the start of treatment, ≥3 months since the last treatment, and they did not have a relapse for ≥6 months after the sample was obtained.

**IHC and triple fluorescence multispectral imaging.** Formalin-fixed, paraffin-embedded tissue sections (3 μm) were deparaffinized and rehydrated, followed by antigen retrieval. For single staining IHC, tissues were stained with antibodies targeting YKL-40 and MMP-9 kinetics experiments, GM-CSF–skewed macrophages were generated and the supernatants were collected every 48 hours, with the final collection on day 8 for ELISAs.

Small interfering RNA (siRNA) knockdown of YKL-40. Monocyte-derived macrophages were generated in the presence of GM-CSF. On day 6, macrophages were harvested and transfected with YKL-40 siRNA (assay ID s2999, Silencer Select; ThermoFisher) or nontargeting control siRNA (catalog no. 4390843, Silencer Select; ThermoFisher) using INTERFERin (Polyplus Transfection). After 24 hours, the medium was replaced with fresh complete medium containing GM-CSF and incubated for 24 hours. The medium was then refreshed with complete medium containing GM-CSF with or without LPS. After 24 hours, medium was collected for ELISA and cells were lysed for RNA extraction and quantitative polymerase chain reaction analysis.

**Tube formation assay.** Human microvascular endothelial cells (HMVECs; Lonza) were treated with medium only, 150 ng/ml YKL-40 (Organon; MSD), 1,500 ng/ml YKL-40, or 20 ng/ml VEGF (PeproTech) in triplicate. HMVECs were cultured for 16 hours and then scanned on a TissueFAXS system (TissueGnostics). Tube formation was assessed by counting the number of visible enclosed fields in a blinded manner.

**Flow cytometric analysis.** HMVECs were stained for expression of endothelial cell marker CD31, IL-13Ra2, and VEGF receptor (VEGFR) (all from Miltenyi Biotec). Three technical replicates containing the 3 markers were compared to “fluorescence minus one” controls, in which either IL-13α2 or VEGFR antibody was omitted.

**Statistical analysis.** To analyze the differences between YKL-40 expression in different layers of the vessel wall and the results for GM-CSF–skewed macrophages and M-CSF–skewed macrophages from the same donor, the paired Wilcoxon signed rank test was used. Correlation analyses were performed with Spearman’s correlation. To analyze the difference between groups in the tube formation assay, one-way analysis of variance with Tukey’s post hoc test was used.

**RESULTS**

Elevation of serum levels of YKL-40 in GCA patients, without normalization of YKL-40 levels after GC treatment. To unravel the dynamics of YKL-40 in GCA patients over time, we first examined serum levels of YKL-40. In this expansion of our previous work (7), serum YKL-40 levels were confirmed to
Serum levels of YKL-40 and interleukin-6 (IL-6) in patients with giant cell arteritis (GCA) and healthy controls (HCs). A cross-sectional analysis of serum levels of YKL-40 (A) and IL-6 (B) was conducted in treatment-naive GCA patients (n = 51) and healthy controls (n = 42), and a longitudinal analysis of serum levels of YKL-40 (A) and IL-6 (B) was conducted in matched samples from GCA patients at baseline (n = 51), 1 year after the start of glucocorticoid treatment (n = 42), and at the time of treatment-free remission (TFR; n = 17). Shading indicates the interquartile range (IQR) in healthy controls. Symbols represent individual subjects; horizontal lines show the median. In the cross-sectional analysis, P values were determined by Mann-Whitney U test. In the longitudinal analysis, P values were determined by Wilcoxon’s signed rank test. NS = not significant. Color figure can be viewed in the online issue, which is available at http://onlinelibrary.wiley.com/doi/10.1002/art.41887/abstract.
macrophages compared to M-CSF-skewed macrophages (Supplementary Figure 4, available on the Arthritis & Rheumatology website at http://onlinelibrary.wiley.com/doi/10.1002/art.41887/abstract), consistent with previous studies (27,28), in both GCA patients and healthy controls. Our data suggest an altered GM-CSF/M-CSF signaling sensitivity in monocyte/macrophages from GCA patients compared to healthy controls.

Figure 2. YKL-40 expression in CD206+MMP-9+ macrophage-rich areas in inflamed medium- and large-sized arteries from patients with giant cell arteritis (GCA). A, Temporal artery biopsy (TAB) specimens from treatment-naive GCA patients were stained for detection of YKL-40 by immunohistochemistry (IHC). Right panels are higher-magnification views of the boxed area, showing expression of YKL-40, CD206, and matrix metalloproteinase 9 (MMP-9) within the same region of the temporal artery biopsy. B, Double staining for YKL-40 and the transcription factor PU.1, which is predominantly expressed by macrophages, indicated that YKL-40 was mainly expressed by macrophages. The bottom boxed area is a higher-magnification view of the top boxed area, showing YKL-40 staining in macrophages. C, Aortas from patients with GCA-related aortic aneurysm were stained for detection of YKL-40 by IHC. Right panels are higher-magnification views of the boxed area, showing expression of YKL-40, CD206, and MMP-9. A pattern of YKL-40 production similar to that shown in A was observed within the region of CD206-expressing cells, located at the site of the granuloma in the media of inflamed aortas. D, YKL-40 expression in GCA temporal artery biopsy specimens and aortas was scored semiquantitatively. Expression of YKL-40 was higher in the intima-media region of temporal artery biopsy specimens, but no significant differences were found between layers in the aortas. The intima was not scored in GCA aortas due to a lack of infiltrate. Data are shown as Tukey box plots. Each box represents the 25th to 75th percentiles. Lines inside the boxes represent the median. Lines outside the boxes represent the 75th percentile plus 1.5 times the interquartile range. P values were determined by Wilcoxon’s signed rank test. E–G, IHC staining of GCA temporal artery biopsy specimens was performed. Single staining IHC for CD206 (E), a merged image of triple immunofluorescence staining for CD206, YKL-40, and MMP-9 (F), and overlapping pixels (cyan) indicating colocalization of CD206, YKL-40, and MMP-9 (G) are shown. Results are representative of 12 samples in A and B, 10 samples in C, and 5 samples in E–G.
Strong expression of IL-13Rα2, the receptor for YKL-40, in GCA lesions. Since YKL-40 is highly expressed in GCA lesions, we next investigated the expression of IL-13Rα2, a confirmed receptor for YKL-40 (24,25), in inflamed temporal artery biopsy specimens from GCA patients (n = 12). IHC detection revealed high expression of IL-13Rα2 by endothelial cells, infiltrating leukocytes, vascular smooth muscle cells, and fibroblasts (Figure 4A), which is consistent with previous reports in the literature (19,25,29–31). Semiquantitative scoring of IL-13Rα2 staining demonstrated high expression levels in all 3 layers of the vessel wall, most prominently in the adventitia and media-intima borders (Figure 4B).

Interestingly, when analyzing the expression of IL-13Rα2 in noninflamed temporal arteries with no or few infiltrating cells, a more restricted staining was seen. IL-13Rα2 was only weakly expressed by endothelium and vascular smooth muscle layers in noninflamed temporal artery biopsy specimens from individuals without GCA or PMR (Figure 4C), while IL-13Rα2 was strongly expressed by endothelial cells, vascular smooth muscle cells, and fibroblasts in noninflamed temporal artery biopsy specimens from patients with PET-proven GCA (skip lesions) (Figure 4D) and patients with isolated PMR (Supplementary Figure 5, available on the Arthritis & Rheumatology website at http://onlinelibrary.wiley.com/doi/10.1002/art.41887/abstract). Taken together, our data suggest a role for the YKL-40/IL-13Rα2 signaling axis in GCA lesions.

YKL-40 as an upstream modulator of macrophage MMP-9 production. To assess if YKL-40 is an upstream modulator of the tissue-destructive MMP-9, we studied the kinetics of YKL-40 and MMP-9 production by differentiating monocytes from healthy controls (n = 8) into macrophages in the presence of lipopolysaccharide (LPS) and 20 ng/ml or 100 ng/ml of GM-CSF (Supplementary Figures 6A and B, available on the Arthritis & Rheumatology website at http://onlinelibrary.wiley.com/doi/10.1002/art.41887/abstract). Both concentrations of GM-CSF equally induced the up-regulation of YKL-40 and MMP-9 as the monocytes differentiated into macrophages. Interestingly, the increase in YKL-40 levels preceded the up-regulation of MMP-9 by 2–4 days. Moreover, the increase in YKL-40 production from day 6 to day 8 strongly correlated with...
the increase in MMP-9 production (Supplementary Figure 6C), suggesting that YKL-40 could be an upstream modulator of MMP-9 production.

To confirm the potential role of YKL-40 as an upstream signal for MMP-9 production in macrophages, we performed siRNA-mediated knockdown of YKL-40 using monocyte-derived macrophages from healthy controls and GCA patients (n = 3 each), demonstrating a knockdown efficiency of 80–95% for YKL-40 mRNA (Supplementary Figure 7, available on the Arthritis & Rheumatology website at http://onlinelibrary.wiley.com/doi/10.1002/art.41887/abstract). This knockdown in turn led to an 80–95% reduction in YKL-40 protein levels compared to nonbinding siRNA control (Figure 5A). Interestingly, YKL-40 knockdown reduced MMP-9 protein levels by 10–50% when compared to siRNA control (Figure 5B), suggesting that (autocrine/paracrine) MMP-9 secretion by macrophages is partially dependent on YKL-40.

Promotion of endothelial tube formation by YKL-40.

YKL-40 and VEGF likely stimulate neovascularization by interacting with their respective receptors, IL-13Rα2 and VEGFR, both of which are abundantly expressed by HMVECs (Figure 6A). We aimed to confirm the proangiogenic potential of YKL-40 by performing a tube formation assay, which is often used to measure the ability of endothelial cells to form capillary-like structures. Previously, it has been demonstrated that YKL-40 has high angiogenic potential, performing equally as well as VEGF in stimulating HMVEC tube formation (32). Indeed, we demonstrated potential of tube formation in the presence of YKL-40 when compared to unstimulated HMVECs (Figures 6B and C). Moreover, the higher
firm and extend those findings by revealing abundant expression located in the media borders was demonstrated. Our data confirmed receptor for YKL-40 (24,25), is highly expressed in GCA patients. Indeed, it has been reported previously that GM-CSF–skewed macrophages derived from healthy donors produce higher levels of YKL-40 than their M-CSF–skewed counterparts (33). In this study, we also found higher YKL-40 levels in GM-CSF–skewed macrophages (compared to M-CSF–skewed macrophages) derived from monocytes from GCA patients, but not in those from healthy controls. Although the exact reason for this apparent discrepancy is not known, it may relate to shifts in monocyte subset composition in conjunction with altered responsiveness to GM-CSF stimulation. With aging, the proportion of classic monocytes decreases (34), whereas this subset is expanded in GCA patients (35). Since classic monocytes have the highest GM-CSF receptor expression (13), these shifts in monocyte subset composition may underlie a heightened sensitivity to GM-CSF skewing in GCA patients. Supporting this notion, monocyte-derived macrophages from GCA patients also express higher levels of CD206, a marker of GM-CSF skewing (13). Currently, the efficacy of mavrilimumab, a GM-CSF receptor antagonist, is being evaluated for the treatment of GCA (ClinicalTrials.gov identifier: NCT03827018). The first encouraging results of this phase II trial have recently been reported, showing a 62% lower risk of flare by week 26 compared to placebo treatment. It is highly likely that mavrilimumab targets the YKL-40–producing macrophage subset, a concept which warrants further investigation.

Our data further extend the notion that YKL-40 is one of the upstream signals for MMP-9 production by macrophages. Our experiments show that YKL-40 and MMP-9 are produced by the same subset of macrophages in GCA lesions and that knocking down YKL-40 acts as an upstream signal that contributes to macrophage MMP-9 production and exerts potent proangiogenic effects. Taken together, our results provide strong evidence that YKL-40, secreted by CD206+MMP-9+ macrophages and giant cells, mediates vascular pathology in GCA through its ability to stimulate MMP-9 secretion and neoangiogenesis.

The presence of YKL-40 in GCA lesions was first reported in 1999 (16), when expression of YKL-40 by CD68+ macrophages located in the media borders was demonstrated. Our data confirm and extend those findings by revealing abundant expression of YKL-40 predominantly by a specific CD206+MMP-9+ subset of macrophages in the inflamed vessel walls. As recently described by our group, CD206+MMP-9+ macrophages, likely induced by local GM-CSF production, are mainly located in the media and its borders near sites of medial destruction (13). Hence, local GM-CSF production is likely important in skewing this macrophage subset toward YKL-40 production in GCA lesions as well.

Whereas the presence of macrophages in GCA lesions is well established, their functional heterogeneity and associated role in GCA pathology is less well described. In this study, we identified a specific CD206+MMP-9+ subset of macrophages that abundantly produces YKL-40 in the GCA lesions. Moreover, in vitro studies revealed that YKL-40 acts as an upstream signal that contributes to macrophage MMP-9 production and exerts potent proangiogenic effects. Taken together, our results provide strong evidence that YKL-40, secreted by CD206+MMP-9+ macrophages and giant cells, mediates vascular pathology in GCA through its ability to stimulate MMP-9 secretion and neoangiogenesis.

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Instead of VEGF. Additionally, YKL-40 and VEGF combined induced even higher tube formation. Taken together, these results further implicate YKL-40 as playing a role in the inflammatory process in GCA by enhancing MMP-9 production and promoting angiogenesis.

DISCUSSION

Whereas the presence of macrophages in GCA lesions is well established, their functional heterogeneity and associated role in GCA pathology is less well described. In this study, we identified a specific CD206+MMP-9+ subset of macrophages that abundantly produces YKL-40 in the GCA lesions. Moreover, in vitro studies revealed that YKL-40 acts as an upstream signal that contributes to macrophage MMP-9 production and exerts potent proangiogenic effects. Taken together, our results provide strong evidence that YKL-40, secreted by CD206+MMP-9+ macrophages and giant cells, mediates vascular pathology in GCA through its ability to stimulate MMP-9 secretion and neoangiogenesis.

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Indeed, it has been reported previously that GM-CSF–skewed macrophages derived from healthy donors produce higher levels of YKL-40 than their M-CSF–skewed counterparts (33). In this study, we also found higher YKL-40 levels in GM-CSF–skewed macrophages (compared to M-CSF–skewed macrophages) derived from monocytes from GCA patients, but not in those from healthy controls. Although the exact reason for this apparent discrepancy is not known, it may relate to shifts in monocyte subset composition in conjunction with altered responsiveness to GM-CSF stimulation. With aging, the proportion of classic monocytes decreases (34), whereas this subset is expanded in GCA patients (35). Since classic monocytes have the highest GM-CSF receptor expression (13), these shifts in monocyte subset composition may underlie a heightened sensitivity to GM-CSF skewing in GCA patients. Supporting this notion, monocyte-derived macrophages from GCA patients also express higher levels of CD206, a marker of GM-CSF skewing (13). Currently, the efficacy of mavrilimumab, a GM-CSF receptor antagonist, is being evaluated for the treatment of GCA (ClinicalTrials.gov identifier: NCT03827018). The first encouraging results of this phase II trial have recently been reported, showing a 62% lower risk of flare by week 26 compared to placebo treatment. It is highly likely that mavrilimumab targets the YKL-40–producing macrophage subset, a concept which warrants further investigation.

Our data further extend the notion that YKL-40 is one of the upstream signals for MMP-9 production by macrophages. Our experiments show that YKL-40 and MMP-9 are produced by the same subset of macrophages in GCA lesions and that knocking down YKL-40 in vitro differentiated macrophages substantially reduces their MMP-9 production. Previously, YKL-40 was found to enhance production of CCL2 and MMP-9, while YKL-40 gene silencing decreased the expression of these proteins in macrophages in mouse models bearing mammary tumors (15). In these mouse models, neutralization of YKL-40 by administering chitin decreased serum YKL-40 levels and decreased MMP-9 production by isolated splenic T cells and macrophages. MMP-9 is likely an important factor in the pathogenesis of GCA, not only in the context of medial destruction, but also as a mediator of T cell and monocyte invasion into the vessel wall (11). Taken together, our data implicate GM-CSF–skewed CD206+ macrophages in GCA lesions in the production of high levels of YKL-40 that could boost MMP-9 expression in an autocrine or paracrine manner.

This is the first study to demonstrate that IL-13Rα2, a confirmed receptor for YKL-40 (24,25), is highly expressed in GCA lesions. Previous studies have shown that the interaction of
YKL-40 with IL-13Rα2 activates the Akt and ERK pathways, both required for MMP-9 expression (36–39). Although IL-13Rα2 was also found to be expressed by endothelial cells, smooth muscle cells, and fibroblasts in the vessel walls of individuals without GCA, its expression was highly increased in active GCA lesions, predominantly by infiltrating leukocytes. Interestingly, we found that IL-13Rα2 was only weakly expressed in temporal artery biopsy specimens from individuals without GCA or PMR (n = 2), indicating that up-regulation of IL-13Rα2 in vessel walls could be GCA/PMR specific. Further studies with more artery samples from individuals without GCA are warranted to confirm these findings.

Our data also suggest that YKL-40 may be an important mediator of neovascularization in GCA, a process that fuels the inflammatory response. The inflamed arteries of GCA patients show an expanded vasa vasorum, extending into the media and intima layers (40). YKL-40 may be one of the main instigators of this process, together with other proangiogenic molecules such as VEGF and angiopoietin 2 (10). Our tube formation assay confirms previous reports on the proangiogenic capacity of YKL-40 alone and in combination with VEGF, which is also highly expressed in GCA lesions (10,32). YKL-40 is also produced by tumor-associated macrophages, and likely plays a role in tumor angiogenesis and progression (14). Studies by Shao et al and Francescone et al showed increased CD31+ endothelial cell density in conjunction with increased expression of YKL-40 in breast cancer and glioblastoma tumors, respectively (32,41). Moreover, those studies also showed a significant reduction in CD31+ endothelial cell infiltration in tumors in mice treated with YKL-40 siRNA and YKL-40 neutralizing antibody. This tumor-supportive effect is reflected by an association of YKL-40 serum levels with a poor outcome in cancer patients. Consistent with these findings, we previously reported that high serum levels of YKL-40 in baseline GCA patients predicted a longer time to discontinuation of GC treatment (7).

Our data suggest an involvement of YKL-40 in tissue destruction and neoangiogenesis. YKL-40 may signal via IL-13Rα2, a known receptor for YKL-40, which we found to be expressed by endothelial cells at the site of inflammation in GCA. Efforts to silence this receptor using siRNA in vitro led to reduced transcript levels, but unfortunately did not suppress cell surface protein expression, suggesting a long half-life of this receptor (data not shown). Thus, we cannot exclude the possibility that the proangiogenic effects associated with YKL-40 production by GCA lesions contribute to disease progression.
of YKL-40 are mediated via another, not yet identified, receptor (32,41). Further studies are required to definitely prove a role for the YKL-40/IL-13Rα2 axis in neovascularization in GCA.

Although YKL-40 is becoming recognized as an important biomarker of inflammation, few mechanistic studies have been performed to investigate its role in autoinflammatory diseases such as GCA. In this study, we used a variety of approaches to identify the cellular source of YKL-40 and its function. Given the substantial effects of GCs on inflammatory processes, it is important to emphasize that we used tissues and cells from treatment-naïve patients. Although our in vitro studies with cultured macrophages have elucidated YKL-40-mediated effects on MMP-9 production, the tissue microenvironment may interfere with these effects in more complex ways. Hence, further studies are required, in particular using in vivo or ex vivo models to improve our understanding of the role of YKL-40 in GCA pathology.

Given its implication in various pathologic pathways, YKL-40 could be a promising target for treatment in macrophage-driven diseases. A neutralizing antibody targeting YKL-40 has shown potential in reducing angiogenesis and tumor progression (42). Blocking YKL-40 or IL-13Rα2 could also prove to be beneficial for the treatment of GCA. GCs, as well as new treatment options such as tocilizumab, may be able to temporarily repress symptoms in GCA patients (4). However, more emerging evidence has indicated that asymptomatic vessel wall inflammation persists, ultimately leading to relapses in a substantial subset of patients (6–9). The persistently high YKL-40 levels in spite of GC treatment, observed in our previous study (7) and confirmed in this study, suggest ongoing vascular inflammation and remodeling. This may be explained by the notion that YKL-40 expression is driven by a multitude of cytokines, including IL-6, GM-CS, and IFNγ (17,33). While IL-6 signaling may be terminated specifically by treatment with tocilizumab and partially by GC treatment, it appears that GM-CSF and IFNγ production are resistant to both drugs (12,43,44). Moreover, a study by Kunz et al revealed little effect of GC treatment on macrophage YKL-40 expression (33). Taken together, these observations are consistent with the persistence of YKL-40-mediated pathology in the vessel wall.

In conclusion, our findings show that a distinct subset of YKL-40–producing CD206+ macrophages is a characteristic feature of the vasculopathy in GCA. These macrophages may fuel media destruction, vasa vasorum neovascularization, and leukocyte invasion into the vessel wall. This process, likely mediated by the YKL-40/IL-13Rα2 axis, initiates a positive forward loop of proinflammatory and tissue remodeling processes via MMP-9 overexpression. Given its potential to promote several mechanisms involved in vessel wall injury, neutralizing YKL-40 or its upstream pathways may prove to be an interesting treatment option for GCA.

**AUTHOR CONTRIBUTIONS**

All authors were involved in drafting the article or revising it critically for important intellectual content, and all authors approved the final version to be published. Dr. van Sleen had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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**Acquisition of data.** van Sleen, Jiemy, Pringle.

**Analysis and interpretation of data.** van Sleen, Jiemy, van der Geest, Abdulahad, Sandovici, Brouwer, Heeringa, Boots.

**REFERENCES**


