Overexpression of α1-acid glycoprotein in transgenic mice leads to sensitisation to acute colitis

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Background: α1-Acid glycoprotein (α1-AGP) is an acute phase protein in most mammalian species whose concentration rises 2–5-fold during an acute phase reaction. Its serum concentration has often been used as a marker of disease, including inflammatory bowel disease (IBD). High α1-AGP levels were found to have a prognostic value for an increased risk of relapse in IBD.

Aims: To investigate a possible role for increased serum levels of α1-AGP in the development of IBD.

Methods: Dextran sodium sulphate (DSS) 2% was added to the drinking water of transgenic mice, overexpressing the rat α1-AGP gene, to induce acute colitis, thus mimicking the conditions of relapse. Clinical parameters, inflammatory parameters, and histological analyses on colon sections were performed.

Results: Homozygous α1-AGP-transgenic mice started losing weight and showed rectal bleeding significantly earlier than heterozygous transgenic or wild-type mice. Survival time of homozygous transgenic mice was significantly shorter compared with heterozygous and wild-type mice. The higher susceptibility of homozygous α1-AGP-transgenic mice to DSS induced acute colitis was also reflected in higher local myeloperoxidase levels, higher inflammation scores of the colon, and higher systemic levels of interleukin 6 and serum amyloid P component. Local inflammatory parameters were also significantly different in heterozygous transgenic mice compared with wild-type mice, indicating a local dosage effect. In homozygous transgenic mice, significantly higher amounts of bacteria were found in organs but IgA levels were only slightly lower than those of control mice.

Conclusion: Sufficiently high serum levels of α1-AGP result in a more aggressive development of acute colitis.

MATERIALS AND METHODS

Mice

Rat α1-AGP-transgenic mice were generated as described previously13 by injecting genomic DNA into (C57BL/6xDBA/2)F1 zygotes; the resulting transgenic mice were backcrossed eight generations into a C57BL/6 background. Heterozygous transgenic mice from the line 9.5-5 constitutively produce about 2 mg/ml α1-AGP. This is 10-fold more than wild-type animals. The colony was propagated by breeding heterozygous transgenic mice with C57BL/6 female mice; the offspring, containing heterozygous transgenic and wild-type littermates, were genotyped at weaning age using an enzyme linked immunosorbent assay. Blood (100 µl) was collected by retro-orbital bleeding, after which serum was prepared. α1-AGP was purified by phenol extraction14 and coated on the bottom of an enzyme linked immunosorbent assay plate. After washing, rat α1-AGP was detected using an antirat α1-AGP polyclonal antibody (generated by H Baumann in rabbits) (1/1000) and an antirabbit antibody, conjugated to alkaline phosphatase (Sigma Chemical Co., St Louis, Missouri, USA; 1/5000). The antirat α1-AGP antibody did not cross react with mouse α1-AGP. About 50% of the offspring were heterozygous transgenics. A homozygous transgenic breeding line was also propagated. Only female mice of 8–12 weeks were used in the experiments. Both transgenic and control (non-transgenic littermates) mice had comparable body weights. Mice were kept in a conventional air conditioned mouse room with a 12 hour...
light-dark cycle and received food and water ad libitum. Mice were bled by retro-ocular bleeding or heart puncture under ether or tribromoethanol (160 mg/kg) anaesthesia, respectively. Serum was prepared after clotting for 30 minutes at 37°C, removal of the clot, and centrifugation for 15 minutes at 15 000 g.

**Disease model**

Acute colitis was induced by adding 2% DSS to the drinking water (tap water) of homozygous and heterozygous α1-AGP-transgenic and wild-type mice. All mice were weighed daily and checked for gross bleeding. Four days after the start of DSS administration, mice were killed using tribromoethanol (160 mg/kg) and blood was taken by heart puncture. To determine colon length, histological score, and local levels of tumour necrosis factor (TNF) and myeloperoxidase (MPO), the colon was removed and washed with phosphate buffered saline (PBS). The colon was cut longitudinally and its length was measured. The distal third of the colon was cut and fixed in 10% formalin in PBS. Two pieces of colon tissue were cut from the distal part of the colon, weighed, and stored in sterile PBS or buffer A (0.5% hexadecyltrimethylammonium bromide in 50 mM potassium phosphate buffer, pH 6.0) at −20°C to determine local TNF and MPO levels, respectively. Sections of the paraffin embedded material were made longitudinally. Three 5 µm sections were cut at a distance of 20 µm. The sections were stained with haematoxylin-eosin. Histological analysis was performed as described previously in a double blind fashion. Mice were scored individually, each score representing the mean of three sections. Epithelium was scored as 0 (normal morphology), 1 (loss of goblet cells), 2 (loss of goblet cells in large areas), 3 (loss of crypts), and 4 (loss of crypts in large areas). Infiltration was scored as 0 (no infiltrate), 1 (infiltrate around crypt bases), 2 (infiltrate reaching to the lamina muscularis mucosa), 3 (extensive infiltration reaching to the lamina muscularis mucosa, thickening of the mucosa with abundant oedema), and 4 (infiltration of the lamina submucosa). The colitis score of individual mice represents the sum of different histological subscores and had a maximum value of 8. Mice that were not killed four days after the start of DSS administration were scored for survival, weighed daily, and checked for gross bleeding. Six days after DSS administration, blood was taken under light ether anaesthesia by retro-ocular bleeding.

**Reagents**

Bovine serum albumin, bovine α1-AGP, alkaline phosphatase conjugated antirabbit IgG, p-nitrophenyl phosphate, hexadecyltrimethylammonium bromide, and o-dianisidine dihydrochloride were obtained from Sigma Chemical Co. DSS (molecular weight 40 000) was purchased from ICN Pharmaceuticals (Costa Mesa, California, USA). Sheep antiserum to mouse SAP (SAP) was a gift from Dr S. Massazza (Univ of California at San Diego, San Diego, California, USA). Goat antiserum to IgA, alkaline phosphatase conjugated goat antiserum to IgA, and a mouse IgA standard were supplied by Southern Biotechnology Associates (Birmingham, Alabama, USA).

**MPO determination**

MPO activity was measured as previously described. Briefly, tissue samples were weighed and homogenised by sonication in buffer A (0.5% hexadecyltrimethylammonium bromide in 50 mM potassium phosphate buffer, pH 6.0). Homogenates were subjected to three freeze/thaw cycles of five minutes each. After centrifugation for 20 minutes, 20 µl of the supernatant of each sample were mixed with 280 µl of buffer B (0.167 mg/ml o-dianisidine dihydrochloride plus 0.0005% H₂O₂ in 50 mM potassium phosphate buffer, pH 6). After 20 minutes, absorbance was measured spectrophotometrically at 490 nm. Pure human MPO was used as a standard. To express MPO levels per mg of protein, protein determination was performed on the same sample according to a method described previously.

**IgA determination**

To isolate faecal IgA, three fresh faecal pellets were weighed and dissolved overnight at 4°C in 1 ml of faeces dissolving solution (0.05% NaN₃ and 10% fetal calf serum in PBS). Faeces were mixed by shaking; after high speed centrifugation, supernatant was collected and stored at −20°C until use. IgA ELISA was performed using microtitre plates coated overnight with a 1/1000 dilution of goat antiserum to IgA. After washing, free places were blocked using 1% bovine serum albumin solution in PBS (one hour at 37°C). Samples and a standard were titrated in 1/3 steps in the assay and incubated at 37°C for one hour. After washing, a second antibody (alkaline phosphatase conjugated goat antiserum to IgA) was added in 1/1000 dilution; plates were incubated for one hour at 37°C. The assay was developed using p-nitrophenylphosphate: absorbance was measured at 405 nm.

**Measurement of serum parameters**

TNF was measured in a cytotoxic assay on WEHI 164 clone 13 cells. Briefly, serial dilutions of samples and TNF standards were incubated with cells in 96 well microtitre plates (30 000 cells/well) in the presence of 1 µg/ml of actinomycin D. After 18 hours of incubation, the number of surviving cells was determined with 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl-tetrazolium bromide (detection range of 0.1 µg/ml). IL-6 was determined as described previously. IL-6 dependent 7T1D1 cells were cultured in 96 well microtitre plates (7000 cells/well) in the presence of medium, serial dilutions of serum, or a murine IL-6 standard. After three days of culture, the number of living cells was determined in a hexosaminidase colorimetric assay; titres were assigned by comparing dilutions of samples and standard needed to obtain half maximal growth of 7T1D1 cells. SAP was measured by a sandwich ELISA, as previously described. Briefly, microtitre plates were coated overnight with a 1/1000 dilution of sheep antiserum to SAP. After washing, free places were blocked using 1% bovine serum albumin solution in PBS (one hour at 37°C). Serum and a standard were diluted 25-fold and titrated in 1/5 steps in triplicate, after which they were incubated at 37°C for one hour. After washing, a second antibody (rabbit antiserum to SAP) was added in a 1/5000 dilution; plates were incubated for one hour at 37°C, after which an antirabbit antibody (alkaline phosphatase conjugated) was added and incubated for another hour at 37°C. The assay was developed using p-nitrophenylphosphate; absorbance was measured at 405 nm.

Rat and mouse AGP were quantitated by rocket immunoelectrophoresis using specific non-cross reactive polyclonal antibodies and appropriate standards previously described.

**Bacterial count**

Mice were killed by cervical dislocation and perfused with 10 ml of sterile PBS to flush the blood out of the organs. Organs were removed aseptically and weighed. For homogenisation, the liver was diluted (w/v) twofold; spleen, kidney, colon, and lung were diluted (w/v) 10-fold. Suspensions were diluted and plated on sterile Luria broth. After overnight incubation at 37°C, colony forming units were determined and expressed as CFU/mg tissue.

**Statistics**

Mean (SD) values were compared using an unpaired Student’s t test, with Welch’s correction in case of non-homogeneous variances. Survival curves (Kaplan-Meier plots) were compared using a log rank test, and final outcomes using Fisher’s exact test. p<0.05 was considered statistically significant.
RESULTS

Clinical symptoms during DSS induced colitis

After administration of 2% DSS to the drinking water of homozygous and heterozygous $\alpha_1$-AGP transgenic mice and to wild-type littermates, mice were weighed daily and stools were checked for the presence of blood. This was done until the onset of the experiment. Eight days after DSS administration, lethality was 6/6, 1/6 (p=0.0034), and 0/6 (p=0.0005), respectively.

Local inflammatory parameters

MPO concentration was determined, as a measure of neutrophil influx, on a distal piece of the colon of control mice from each group before DSS administration and four days after DSS administration. In the latter case, there was a significant increase in MPO levels in all three groups of mice compared with control levels (p<0.001). Moreover, there was also a significant difference after DSS administration between homozygous and heterozygous transgenic mice, between homozygous transgenic and wild-type mice, and between heterozygous transgenic and wild-type mice (p<0.0001) (fig 2). TNF levels were determined on colon samples of control mice of each group before and after four days of DSS administration. Local TNF was not detectable (results not shown).

Finally, inflammation of the distal colon was scored histologically in a double blind fashion four days after DSS administration. A significant increase in inflammation score was found compared with that of heterozygous transgenic mice (p=0.0241) and wild-type (p=0.0035) mice. The difference in weight loss was most pronounced starting from day 3 (p<0.0004 for difference in weight between homozygous and heterozygous transgenic mice, and homozygous and wild-type mice on days 3, 4, 5, and 6). Homozygous transgenic mice started to show gross bleeding on day 2. On day 3, the number of homozygous transgenic mice that showed gross bleeding was significantly higher than in wild-type mice (p=0.0032); on day 5, all homozygous transgenics showed gross bleeding (p=0.0033 compared with wild-type mice). In heterozygous and wild-type mice, gross bleeding was observed on days 3 and 4, respectively; all mice showed gross bleeding on days 7 and 8, respectively. The number of homozygous transgenic mice that showed gross bleeding was significantly different compared with that of wild-type mice on days 6 and 7 (p=0.0202 and p=0.0228, respectively) (table 1). Survival of homozygous transgenic mice was significantly reduced compared with heterozygous and wild-type mice (p<0.0001). Homozygous transgenic mice all died between days 4 and 8 while heterozygous and wild-type mice died between days 7 and 13, and days 8 and 12, respectively (fig 1B).

Exogenous AGP administration in wild-type mice also resulted in significant enhanced weight loss and earlier lethality compared with control mice: six days after DSS administration, wild-type mice which received two intraperitoneal injections (on days 0 and 3) of 10 mg of bovine $\alpha_1$-AGP had a mean weight of 14.6 (0.2) g, mice which received two injections of 5 mg $\alpha_1$-AGP had a mean weight of 15.9 (0.5) g, and wild-type mice receiving no $\alpha_1$-AGP had a mean weight of 17.8 (0.1) g (n=6 for each group; p<0.001 for each group compared with one another). All mice had the same weight at the onset of the experiment. Eight days after DSS administration, lethality was 6/6, 1/6 (p=0.0034), and 0/6 (p=0.0005), respectively.

Table 1 Appearance of gross bleeding in mice [%] during dextran sodium sulphate treatment.

<table>
<thead>
<tr>
<th>Day</th>
<th>Homozygous transgenic</th>
<th>Heterozygous transgenic</th>
<th>Wild-type</th>
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<tbody>
<tr>
<td>0</td>
<td>0 [n=36]; NS</td>
<td>0 [n=38]; NS</td>
<td>0 [n=30]</td>
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<tr>
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<td>0 [n=38]; NS</td>
<td>0 [n=30]</td>
</tr>
<tr>
<td>3</td>
<td>25 [n=36]; ***</td>
<td>3 [n=38]; NS</td>
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<td>19 [n=38]; NS</td>
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<td>8</td>
<td>ND [n=0]</td>
<td>100 [n=13]; NS</td>
<td>100 [n=10]</td>
</tr>
</tbody>
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Significance was calculated using a $\chi^2$ test. All values were compared with wild-type mice. *p<0.05, **p<0.01, ***p<0.001.
for all three groups of mice was found compared with control mice before DSS administration (p=0.0001, p=0.0003, and p=0.044 for homozygous transgenic, heterozygous transgenic, and wild-type mice, respectively). There was also a significant difference between the various groups four days after DSS administration. Homozygous transgenic mice had a significantly higher inflammatory score than heterozygous transgenic (p<0.0001) and wild-type mice (p<0.0001). Moreover, heterozygous transgenic mice also had a significantly higher inflammation score compared with wild-type mice (p=0.0056) (fig 3A). A representative example of colon sections of negative controls, and wild-type, homozygous, and heterozygous transgenic mice four days after 2% DSS administration is shown in fig 3B. Negative controls showed no signs of crypt damage or inflammatory infiltrate. Wild-type mice showed only mild inflammation consisting of local, and in some cases more general, loss of goblet cells and inflammatory infiltrate localised to the crypt base. In heterozygous transgenic mice, crypt damage was in most cases confined to general loss of goblet cells or local crypt loss while inflammatory infiltrate extended from the crypt base to the lamina muscularis mucosa, with or without signs of oedema. In homozygous transgenic mice, crypt damage ranged from local to general crypt destruction; inflammatory infiltrate reached the lamina muscularis mucosa, with abundant oedema, or even the submucosa. In all cases, inflammatory infiltrate consisted of a mixture of granulocytes and lymphocytes.

**Systemic inflammatory parameters**

Four days after DSS administration, half of the mice in each group were killed and blood was taken by heart puncture. The surviving mice were bled by retro-ocular bleeding six days after DSS administration. Cytokine, SAP, and mouse or rat AGP levels were determined in serum samples as a systemic measure of inflammation. IL-6 levels were increased in the three groups of mice four days after DSS administration compared with control mice (p=0.0004 for homozygous transgenic mice and p=0.0159 for wild-type mice); the increase in IL-6 concentration in the serum of heterozygous transgenic mice was not statistically significant. There was also a significant difference in IL-6 levels four days after DSS administration between homozygous transgenic and heterozygous transgenic mice on the one hand and between homozygous transgenic and wild-type mice on the other (p=0.0026 and p=0.0002, respectively) (fig 4). TNF was not detected in serum samples, neither four days nor six days after DSS administration (results not shown). SAP levels in serum four days after DSS administration were significantly increased in homozygous transgenic mice (p=0.0059) but not in heterozygous transgenic and wild-type mice. Six days after DSS administration there was a significant increase in SAP levels in homozygous and heterozygous transgenic mice. The increase in SAP levels in wild-type mice was not statistically significant. We also found a significant difference in SAP levels six days after DSS administration compared with four days after DSS administration in the three groups of mice (p<0.0001, p=0.0042, and p=0.0037 for homozygous transgenic, heterozygous transgenic, and wild-type mice, respectively). Among the groups, there was a significant difference four and six days after DSS administration between homozygous and heterozygous transgenic mice on the one hand and between homozygous and wild-type mice on the other (p<0.0001 for all) (fig 5A). Mouse AGP levels in wild-type mice were increased significantly after DSS treatment (fig 2). Negative controls showed no signs of crypt damage or inflammatory infiltrate. Wild-type mice showed only mild inflammation consisting of local, and in some cases more general, loss of goblet cells and inflammatory infiltrate localised to the crypt base. In heterozygous transgenic mice, crypt damage was in most cases confined to general loss of goblet cells or local crypt loss while inflammatory infiltrate extended from the crypt base to the lamina muscularis mucosa, with or without signs of oedema. In homozygous transgenic mice, crypt damage ranged from local to general crypt destruction; inflammatory infiltrate reached the lamina muscularis mucosa, with abundant oedema, or even the submucosa. In all cases, inflammatory infiltrate consisted of a mixture of granulocytes and lymphocytes.

**Figure 2** Local myeloperoxidase (MPO) levels after dextran sodium sulphate (DSS) treatment. MPO levels were determined in colon samples of homozygous α₁-AGP-transgenic (n=18), heterozygous α₁-AGP-transgenic (n=19), and wild-type mice (n=15) four days after administration of 2% DSS and compared with negative controls of the corresponding genotype (n=5 for each group). Statistical significance was assessed compared with homozygous transgenic mice. ***p<0.001.

**Figure 3** (A) Histological score after dextran sodium sulphate (DSS) treatment. Four days after 2% DSS treatment, the histological score was determined from the distal part of the colon from homozygous α₁-AGP-transgenic (n=18), heterozygous α₁-AGP-transgenic (n=19), and wild-type mice (n=15) and compared with negative controls of the corresponding genotype (n=5 for each group). Statistical significance values are based on homozygous and heterozygous transgenic versus wild-type mice, and homozygous versus heterozygous transgenic mice: ***p<0.01, ***p<0.001. (B) Representative distal colon sections (100×) stained with haematoxylin-eosin. (a) Section of a negative control (no DSS treatment) showing normal crypt morphology, with crypt bases resting on the lamina muscularis mucosa, and no inflammatory infiltrate. (b) Section of a wild-type mouse four days after DSS treatment. There is local loss of goblet cells and some inflammatory infiltrate at the crypt base which is no longer resting on the lamina muscularis mucosa. (c) Section of a heterozygous transgenic mouse showing local crypt destruction and inflammatory infiltrate reaching to the lamina muscularis mucosa. (d) Section of a homozgygous transgenic mouse with total destruction of crypt structure and inflammatory infiltrate reaching into the submucosa.
The inflammatory infiltrate mainly consists of MPO positive granulocytes. The earliest histological observation is loss of goblet cells, following DSS administration include haemocult positive and cytotoxicity. It was found that high serum concentrations of α1-AGP in the development of acute colitis. We found that during DSS administration, homozygous α1-AGP-transgenic mice started to show clinical signs of illness much earlier than heterozygous transgenic or wild-type controls. Weight loss and gross bleeding appeared significantly earlier in transgenic mice compared with wild-type mice, and survival of homozygous transgenic mice was significantly reduced compared with heterozygous transgenic and wild-type mice. The clinical data clearly show a difference in response to DSS between homozygous transgenics on the one hand and heterozygous transgenics and wild-type mice on the other. However, except for a minor but statistically significant difference in appearance of gross bleeding, there was no significant difference in clinical parameters between heterozygous transgenics and wild-type mice. The fact that...
TNF bioactivity in colon or serum samples. Demonstrated by several investigators, the colon samples, even using a very sensitive bioassay (detecting inflammation/pathology than wild-type mice, homozygous not detect any TNF bioactivity in serum samples both in control groups. However, there was no difference in IgA levels between the three groups of mice. Macrophages play an important role in the acute DSS model as they phagocytose DSS, leading to activation of macrophages, which can contribute to tissue damage. As α1-AGP can stimulate macrophages to release proinflammatory cytokines such as IL-1, this could result in a positive feedback loop; the high local concentration of α1-AGP could have an exponential effect on cytokine release and could stimulate leukocyte recruitment and activation whereby more macrophages and other inflammatory cells such as neutrophils are activated and contribute to tissue damage. Indeed, we have shown that there was more MPO in transgenic mice compared with wild-type mice.

In conclusion, we have shown that α1-AGP-transgenic mice have an increased susceptibility to DSS induced colitis compared with wild-type mice. Clinically and systemically there is little difference in the parameters observed between homozygous transgenic and wild-type mice. However, when considering local parameters, such as MPO levels and inflammation score, there was a dosage effect of α1-AGP. Homozygous transgenic mice are more susceptible than heterozygous transgenic mice; the latter are clearly more susceptible to DSS induced colitis than wild-type mice. Our results suggest that high levels of α1-AGP can have a synergistic effect with stimuli that can provoke colitis.

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