HOST RESPONSE TO INFECTION

Susceptibility of *Helicobacter pylori* and its urease activity to the peroxidase-hydrogen peroxide-thiocyanate antimicrobial system

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The susceptibility of *Helicobacter pylori* to the antimicrobial system involving lactoperoxidase, hydrogen peroxide and thiocyanate was investigated. The inhibitory effect of the system on the urease activity of *H. pylori*, which plays a role in its colonisation of the stomach, was also investigated. Twelve *H. pylori* strains examined, including 10 clinical isolates, were all inhibited by the peroxidase system in brain-heart infusion broth supplemented with fetal calf serum, but to different extents. The killing effect was observed within 3 h. Although bacterial viability recovered afterwards, there was still a clear difference between cultures incubated in the presence of the complete system and controls incubated in the absence of lactoperoxidase, after incubation for 24 h. The urease activity and viability of *H. pylori* were both inactivated by this system in phosphate buffer. These effects were dependent on the concentrations of both lactoperoxidase and hydrogen peroxide and were abolished by the addition of cysteine. Furthermore, these effects were observed when bovine lactoperoxidase was replaced by recombinant human lactoperoxidase or native or recombinant human myeloperoxidase. The peroxidase system found in saliva and milk may contribute to the host defence against *H. pylori* infection and inhibition of transmission via the oral route.

Introduction

*Helicobacter pylori*, a spiral-shaped gram-negative bacterium with flagella [1], is the cause of human gastritis, peptic gastric ulcers and duodenal ulcers [2]. Recent epidemiological and animal studies have suggested an association between *H. pylori* and gastric cancer, including adenocarcinoma and gastric lymphoma [2]. The urease produced by *H. pylori* is known to be an essential factor for its colonisation of the stomach [1]. Besides neutralising gastric acid, some other roles of this enzyme in *H. pylori* colonisation and pathogenesis have been suggested. The hydrolysis of urea by cytoplasmic urease results in energy generation in the form of a proton-motive force which drives flagellar rotation, allowing bacterial motility in the mucus gel layer of the stomach [1, 3]. The formation of monochloramine from ammonia produced by *H. pylori* urease and neutrophil-derived hypochlorous acid have been suggested to play an important role in gastric mucosal injury [4, 5]. Although the precise route of transmission and the natural reservoir of *H. pylori* remain unknown, recent clinical studies support the existence of gastro–oral and oral–oral pathways of transmission [6]. *H. pylori* has been isolated successfully from the oral cavity by culture [6]. In a study employing the PCR method in which 42 patients were examined, *H. pylori* DNA was identified in dental plaque of 97% of the patients and in the saliva of 55% of the patients, showing a distribution relatively independent of the infection status of the stomach [7].

Human saliva, which continuously bathes the oral mucosa and teeth, contains various antimicrobial factors such as lysozyme, lactoferrin, peroxidases and secretory IgA [8]. Two different haem-containing peroxidases, salivary peroxidase secreted from the salivary gland and myeloperoxidase (MPO) derived from neutrophil polymorphonuclear leucocytes (neutrophils), have been identified in whole saliva [9, 10]. Recent genetic studies have revealed that salivary peroxidase is another product of the gene encoding lactoperoxidase (LPO) [11–14], a secretory peroxidase.
found in breast milk [15–17]. LPO is a nonmoneric
glycoprotein that varies in molecular mass from c. 80
to 100 kDa [9, 13, 15–17]. MPO is a tetrameric
glycoprotein consisting of two 59-kDa heavy chains
and two 13.5-kDa light chains in its mature form and
found in the azurophilic granules of neutrophils [18].
These enzymes catalyse the hydrogen peroxide (H₂O₂)-
dependent oxidation of thiocyanate (SCN⁻) to yield
the hypothiocyanite anion (OSCN⁻) with inhibitory activ-
ity against a wide variety of micro-organisms including
gram-positive and gram-negative bacteria, fungi and
viruses [19–23]. The product, OSCN⁻, reacts with
microbial sulph-hydrlys [24] and inhibits various cell-
ular processes such as glycolysis [25, 26], membrane
transport of sugars and amino acids [27, 28] and
respiration [29, 30]. It has been estimated that human
saliva samples under resting and stimulated conditions
contain OSCN⁻ at average concentrations of 61 and
34 μM, respectively [31]. Therefore, it is of interest to
study the effects of the peroxidase antimicrobial sys-
tem, a natural component of secretions such as saliva
and milk, against H. pylori. This study reports for the
first time the influence of the peroxidase-H₂O₂-SCN⁻
antimicrobial system on the viability and urease activity of H. pylori.

Materials and methods

Bacteria and growth conditions

H. pylori ATCC 43504 and 43629 were obtained from the
American Type Culture Collection (Rockville, MD, USA). Ten different human clinical isolates of H. pylori isolated from gastric tissue of H. pylori-positive patients treated at Mie University Hospital (Mie, Japan), of which four isolates had been used in a previous study [32], were used. The bacteria were
grown either on Trypticase Soy Agar (Becton Dick-
inson) supplemented with defibrinated horse blood
(Nihon Biosupp. Center, Tokyo, Japan) 5% (TSB) or
Brain-Heart Infusion Broth (Difco) supplemented with
fetal calf serum (Nihon Biosupp. Center) 5% (BHI-
serum). The cultures were incubated at 37°C under
micro-aerobic conditions (CO₂ 10%).

Peroxidases

LPO purified from bovine milk (A₄₅₀/A₂₈₀ = 0.90) was
purchased from Sigma. Native human MPO purified
from leucocytes (A₄₃₃/A₂₈₀ = 0.73) was obtained from
Athens Research and Technology (Athens, GA, USA).
Recombinant human LPO and MPO were expressed in a
baculovirus-insect cell system and purified according
to the procedure described by Shin et al. [13].

Peroxidase system

The LPO system composed of bovine LPO 8 μg/ml,
0.6 mM H₂O₂ and 0.66 mM SCN⁻ was tested to assess
its influence on the growth of H. pylori in 12-well
plates containing BH1-serum broth, with a total volume
of 2 ml/well. The wells were inoculated with H. pylori
cells, preincubated in BH1-serum broth, at a cell density
of c. 10⁶ or 10⁷ cfu/ml. The LPO system was initiated
by the addition of H₂O₂ to the wells containing all
other components pre-warmed to 37°C. The plates were
incubated under micro-aerobic conditions at 37°C and
the number of viable bacterial cells was determined at
indicated times by plating on TSA agar after appropri-
te dilution in phosphate-buffered saline (PBS; 138 mM
NaCl, 2.7 mM KCl, 10 mM phosphate buffer, pH 7.4). The colonies formed on the plates were
counted after incubation under micro-aerobic condi-
tions at 37°C for 4 days. The detection limit in deter-
mination of the number of H. pylori cells was log₁₀
1.70 cfu/ml.

Urease activity

The LPO system with the same composition was also
tested to assess its influence on the urease activity of
H. pylori in 50 mM sodium phosphate buffer, pH 6.6.
H. pylori cells were treated at a cell density of c.
10⁷ cfu/ml under micro-aerobic conditions at 37°C for
1 h. The reaction of the LPO system was terminated by
mixing with an equal volume of 10 mM sodium azide.
Sodium azide added at this concentration did not show
any inhibitory effect on the urease activity. As a ref-
ference, urease purified from Jack bean (Wako Pure
Chemical, Osaka, Japan) was also treated with the
system at a concentration of 1 mg/ml. After the treat-
ment, the urease activity in the bacterial suspension or
the enzyme solution was determined without any further
treatment. Measurement of urease activity was
based on the phenol-hypochlorite reaction as described
by Takebe and Kobayashi [33]. The activity of urease is
expressed as international units (IU), where one unit is
defined as the amount of enzyme hydro-
lysing 1 μmol of urea/min at 37°C. The influence of
the concentrations of LPO and H₂O₂, the influence of
cysteine added as L-cysteine hydrochloride mono-
hydrate (Kanto Chemical, Tokyo, Japan) and the effect of
replacement of bovine LPO with recombinant human
LPO, or native or recombinant human MPO were also
examined. The number of viable bacterial cells in the
reaction mixture of the peroxidase system was also
determined without addition of sodium azide by
serially diluting the mixture in PBS and plating the
diluted samples on TSA agar as described above.

Results

Effects of the peroxidase system on the growth of H. pylori

The 12 H. pylori strains examined were all inhibited by
the LPO system in BH1-serum broth, but to different
extents (Table 1). Among them, clinical isolate no. 32
was most susceptible to the LPO system, as the number of
viable bacterial cells was reduced by more than
Table 1. Effect of the LPO system on the number of H. pylori in BHI-serum broth

<table>
<thead>
<tr>
<th>Strain no.</th>
<th>Mean (SD) bacterial number (log_{10} cfu/ml)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATCC 43504</td>
<td>7.73 (0.02)</td>
</tr>
<tr>
<td>ATCC 43629</td>
<td>8.34 (0.06)</td>
</tr>
<tr>
<td>Clinical isolates</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>7.90 (0.06)</td>
</tr>
<tr>
<td>3</td>
<td>8.08 (0.07)</td>
</tr>
<tr>
<td>19</td>
<td>7.97 (0.04)</td>
</tr>
<tr>
<td>32</td>
<td>7.98 (0.08)</td>
</tr>
<tr>
<td>33</td>
<td>8.11 (0.03)</td>
</tr>
<tr>
<td>38</td>
<td>7.98 (0.07)</td>
</tr>
<tr>
<td>A</td>
<td>8.85 (0.22)</td>
</tr>
<tr>
<td>B</td>
<td>8.10 (0.04)</td>
</tr>
<tr>
<td>C</td>
<td>7.17 (0.09)</td>
</tr>
<tr>
<td>D</td>
<td>7.49 (0.03)</td>
</tr>
</tbody>
</table>

The BHI-serum broth was inoculated with H. pylori cells at c. 10^5 cfu/ml in the case of each strain examined and the cultures were incubated with the LPO system composed of bovine LPO 8 mg/L, 0.6 mM H_2O_2, and 0.66 mM SCN\textsuperscript{−}. After incubation at 37°C for 24 h under micro-aerobic conditions, the number of viable bacteria was compared with that in control cultures incubated under the same conditions in the absence of LPO.

Results represent the mean (SD) of three experiments.

Table 2. Effects of the LPO system on the urease activity and viability of H. pylori in phosphate buffer

<table>
<thead>
<tr>
<th>Condition</th>
<th>Urease (mU/μg protein)³</th>
<th>Urease (mU/10^9 cfu of inoculum)³</th>
<th>Mean (SD) bacterial number (log_{10} cfu/ml)³</th>
<th>Urease (mU/10^9 cfu of inoculum)³</th>
<th>Mean (SD) bacterial number (log_{10} cfu/ml)³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>95.2</td>
<td>5.45</td>
<td>7.06 (0.05)</td>
<td>2.71</td>
<td>7.21 (0.06)</td>
</tr>
<tr>
<td>LPO system</td>
<td>0.00</td>
<td>0.03</td>
<td>&lt;1.70 (….)</td>
<td>0.01</td>
<td>&lt;1.70 (…)</td>
</tr>
<tr>
<td>LPO system with cysteine</td>
<td>100</td>
<td>4.33</td>
<td>6.97 (0.07)</td>
<td>1.42</td>
<td>7.09 (0.17)</td>
</tr>
</tbody>
</table>

Jack bean urease at 1 mg/ml or cells of H. pylori ATCC 43504 or clinical isolate no. 19 at c. 10^5 cfu/ml were treated with the LPO system with or without 10 μmol cysteine in 50 mM phosphate buffer, pH 6.6, at 37°C for 1 h under micro-aerobic conditions, controls did not contain H_2O_2. Urease activity and the number of viable bacteria in the mixture were assayed as described in the text. Results represent the mean of three experiments.

Effects of the peroxidase system on the urease activity and viability of H. pylori in phosphate buffer

As ammonia was detected in BHI-serum broth at a level that significantly interfered with the urease assay, phosphate buffer was used to assess the effect of the LPO system on the urease activity of H. pylori. The urease of H. pylori and the urease purified from Jack bean were both almost completely inactivated by the LPO system (Table 2). The inactivation of urease was partially abolished by the addition of cysteine hydrochloride, suggesting that such inactivation is due to the oxidation of functionally important sulph-hydryls of the enzyme. The inactivation of urease by this system was found to be dependent on the concentration of LPO and complete inactivation was achieved at an LPO concentration of 1 mg/L (Fig. 2a). The inactivation of urease was also found to be dependent on the concentration of H_2O_2 and no activity of the H. pylori urease or the Jack bean enzyme remained when treated at an H_2O_2 concentration of 0.3 and 0.01 mM, respectively (Fig. 2b).

H. pylori lost viability in phosphate buffer containing the complete LPO system; the number of viable cells decreased to a level below the detection limit (Table 2). Cysteine hydrochloride protected H. pylori from the bacterial effect of the LPO system, suggesting that the oxidation of bacterial sulph-hydryls by OSCN\textsuperscript{−} may occur. The killing effect of this system was found to be dependent on the concentration of LPO and the number of viable cells decreased to a level below the detection limit at an LPO concentration of 1 mg/L (Fig. 2c). The killing effect was also found to be dependent on the concentration of H_2O_2 and no viable clinical isolate no. 19 was significantly reduced in the presence of SCN\textsuperscript{−} and H_2O_2 when an inoculum of 10^5 cfu/ml was used (Fig. 1d). However, no such decrease in the viability of this strain in the presence of SCN\textsuperscript{−} and H_2O_2 was observed when an inoculum of 10^7 cfu/ml was used (Fig. 1c). No inhibition of strain ATCC 43504 was observed at the same concentration of SCN\textsuperscript{−} and H_2O_2 with an inoculum of 10^5 or 10^7 cfu/ml (Fig. 1a and b).

log_{10} 4 compared with control cells incubated in the absence of LPO. Strain ATCC 43629 was the most resistant, as the number of viable cells was reduced by log_{10} <1. Most H. pylori strains other than ATCC 43629 and clinical isolate no. 3 showed lower viability after exposure to the LPO system for 24 h than that at the time of inoculation, indicating that the LPO system is bactericidal against H. pylori. The type strain ATCC 43504 and clinical isolate no. 19 were used to study the mode of action of the LPO system. The killing effect of the LPO system was observed against both strains within 3 h and the viability recovered afterwards (Fig. 1). However, the number of viable bacteria in the cultures incubated with the complete system was clearly different from that in control cultures incubated in the presence of SCN\textsuperscript{−} only or in the presence of LPO and SCN\textsuperscript{−} only for up to 24 h in the case of strain ATCC 43504 and for up to 48 h in the case of clinical isolate no. 19. The influence of bacterial inoculum size was investigated with two different inocula, with the same concentration (0.6 mM) of H_2O_2 in each instance. The viability of
bacteria were found when treated at an H₂O₂ concentration of 0.6 mM (Fig. 2d).

Effects of peroxidases from different sources

Inhibitory effects of the peroxidase system on the urease activity and viability of *H. pylori* were observed in phosphate buffer when bovine LPO was replaced by recombinant human LPO, or native or recombinant human MPO (Table 3).

Discussion

The results of the present study show that the system composed of peroxidase, H₂O₂ and SCN⁻, which is a natural component of secretions such as saliva and milk, exerts antimicrobial effects against *H. pylori*. The short-lived bactericidal effect of the system on *H. pylori* is in agreement with previous reports of studies with other species of bacteria, in which H₂O₂ was introduced only at the initiation of the reaction [34, 35]. SCN⁻ was used at a concentration of 0.66 mM throughout this study. This concentration of SCN⁻ is within the range reported in human saliva samples (1.21 ± 0.66 m for resting condition and 0.84 ± 0.48 m for stimulated condition) [31]. In a previous study, it was observed that the LPO system with a composition similar to that used in this study (0.66 mM SCN⁻, 0.6 mM H₂O₂ and bovine LPO 8 mg/L in 50 mM phosphate buffer, pH 6.6) yielded OSCN⁻ at concentrations of 171 and 48 μM at 5 and 60 min after the start of the reaction, respectively [30]. These concentrations of OSCN⁻ are also within the range of that reported in human parotid saliva samples collected directly from Stensen’s duct (range 10–210 μM, av-
Fig. 2. Influence of the concentrations of LPO and H$_2$O$_2$ on inactivation of urease and their bactericidal effect against H. pylori. Jack bean urease at 1 mg/ml (●) or cells of H. pylori ATCC 43504 (△) or clinical isolate no. 19 (□) at c. $10^5$ cfu/ml were treated with the LPO system composed of various concentrations of bovine LPO, 0.6 mM H$_2$O$_2$ and 0.66 mM SCN$^-$ in 50 mM phosphate buffer, pH 6.6, at 37°C for 1 h under micro-aerobic conditions (a). In other experiments, bovine LPO was added at 8 mg/L and H$_2$O$_2$ was added at various concentrations (b). Urease activity was assayed as described in the text. Bacterial viability was examined under the same conditions as indicated for panels a and b and the results are shown in panels c and d, respectively. Results represent the mean of two experiments.

Table 3. Effects of LPO and MPO from different sources on the urease activity and viability of H. pylori in phosphate buffer

<table>
<thead>
<tr>
<th>Peroxidase</th>
<th>H. pylori ATCC 43504</th>
<th>H. pylori no. 19</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Urea (mIU/10$^7$ cfu of inoculum)$^a$</td>
<td>Mean (SD) bacterial number (log$_{10}$ cfu/ml)$^a$</td>
</tr>
<tr>
<td>Bovine LPO</td>
<td>0.01</td>
<td>&lt;1.70 . .</td>
</tr>
<tr>
<td>Recombinant human LPO</td>
<td>0.00</td>
<td>&lt;1.70 . .</td>
</tr>
<tr>
<td>Human MPO</td>
<td>0.00</td>
<td>&lt;1.70 . .</td>
</tr>
<tr>
<td>Recombinant human MPO</td>
<td>0.00</td>
<td>2.22 (0.20)</td>
</tr>
<tr>
<td>Control (without peroxidase)</td>
<td>4.09</td>
<td>7.06 (0.05)</td>
</tr>
</tbody>
</table>

Experiments were done under the same conditions as described in Table 2 except that bovine LPO was replaced with recombinant human LPO, or native or recombinant human MPO at the same concentration; controls did not contain peroxidase.

$^a$Results represent the mean of three experiments.

$^b$Results represent the mean (SD) of three experiments.
erase 52 μM) [31]. Therefore, it seems reasonable to extrapolate the results obtained in this study to the conditions in vivo.

It is well known that H₂O₂ in itself has an inhibitory effect on various micro-organisms including H. pylori [36, 37]. Indeed, the viability of clinical isolate no. 19 was significantly reduced in the presence of 0.66 mM SCN⁻ and 0.6 mM H₂O₂ when the strain was incubated at a lower density (10⁵ cfu/ml). As H. pylori is catalase positive [38] and not susceptible to SCN⁻ at the concentration used in this study, a larger amount of endogenous catalase from the higher density of cells (10² cfu/ml) may be needed to diminish the toxicity of H₂O₂ in the case of a strain with high H₂O₂ sensitivity such as clinical isolate no.19. However, most of the results in this study showed that the antimicrobial activity of the product of the reactions catalysed by peroxidases was greater than that of SCN⁻ and H₂O₂.

The results of the present study show that the peroxidase system inactivates ureases from H. pylori and Jack bean. It has been shown that the chemical modification of a cysteine residue near the active site of the urease from Jack bean, or that of Klebsiella aerogenes, can eliminate enzyme activity [39, 40]. A high degree of similarity in the primary structure has been found by comparing the ureases from various bacteria, including H. pylori and K. aerogenes, and the Jack bean urease [41]. Therefore, it seems reasonable to assume that OSCN⁻, a reactive intermediate produced by the peroxidase system, inactivates the urease of H. pylori and that of Jack bean by reacting with an important cysteine residue near the active site. The influence of the LPO system on urease activity of strains ATCC 43629 and clinical isolate no. 3, which were the most resistant to the system in BHI-serum broth, was also examined. The sensitivity of ureases of these strains was quite similar to that observed for ATCC 43504 and clinical isolate no.19 (details not shown). Therefore, urease inactivation by the LPO system is not likely to correlate directly to the bacterial effect of the system. Although the urease of H. pylori is principally involved in neutralising gastric acid, recent studies have suggested some other roles of this enzyme in H. pylori colonisation and pathogenesis, such as a role in flagellar rotation and a role in triggering gastric mucosal injury through the inflammatory response [1, 3–5]. The peroxidase system in secretions may reduce the degree of pathogenesis of H. pylori by inhibiting the urease.

Recent genetic studies have demonstrated that salivary peroxidase is expressed from the chromosomal gene encoding LPO [11–14]. The peroxidase system may exert its antimicrobial effect on H. pylori in the oral cavity, as whole human saliva contains large amounts of LPO and MPO at average concentrations of 1.9 and 3.6 mg/L [10], respectively. The concentration of peroxidases, 8 mg/L, used in most of the experiments of this study is slightly above the sum of LPO and MPO concentrations reported in saliva [10] and it is within the range of total peroxidase estimated in saliva with bovine LPO as a standard [42]. The influence of the LPO concentration was tested and it was found that LPO in amounts as small as 1 mg/L completely abolished both urease activity and the viability of H. pylori in phosphate buffer. Furthermore, saliva contains OSCN⁻, the antimicrobial intermediate produced by the system, at an average concentration ranging from 34 to 61 μM [8, 31]. Although the formation of hypochlorous acid by neutrophil-derived MPO has been suggested to serve as a pathogenic factor of H. pylori causing gastric mucosal injury through an inflammatory response [4, 5], the system composed of MPO, H₂O₂ and SCN⁻ kills the bacteria and can at least contribute to host protection against H. pylori in the early stage of infection. The peroxidase system derived from saliva or milk may be active in the oesophagus and the stomach, as it has been shown that peroxidase activity is not rapidly inactivated in gastric juice [43]. Further clinical studies will be needed to determine the influence of the peroxidase system on H. pylori colonisation.

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References


