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Effect of Cold Starvation, Acid Stress, and Nutrients on Metabolic Activity of Helicobacter pylori

Hans-Olof Nilsson, Jens Blom, Waleed Abu Al-Soud, Åsa Ljungh, Leif P. Andersen, and Torkel Wadström

Department of Medical Microbiology, Dermatology and Infection, Lund University, SE-223 62 Lund, Sweden, and Laboratory for Electron Microscopy, State Serum Institute, and Department of Microbiology, Rigshospitalet, Copenhagen, Denmark

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Helicobacter pylori can transform, in vivo as well as in vitro, from dividing spiral-shaped forms into nonculturable coccoids, with intermediate forms called U forms. The importance of nonculturable coccoid forms of H. pylori in disease transmission and antibiotic treatment failures is unclear. Metabolic activities of actively growing as well as nonculturable H. pylori were investigated by comparing the concentrations of cellular ATP and total RNA, gene expression, presence of cytoplasmic polyphosphate granules and iron inclusions, and cellular morphology during extended broth culture and nutritional cold starvation. In addition, the effect of exposing broth-cultured or cold-starved cells to a nutrient-rich or acidic environment on the metabolic activities was investigated. ATP was detectable up to 14 days and for at least 25 days after transformation from the spiral form to the coccoid form or U form in broth-cultured and cold-starved cells, respectively. mRNAs of VacA, a 26-kDa protein, and urease A were detected by using reverse transcription-PCR in cells cultured for 2 months in broth or cold starved for at least 28 months. The ATP concentration was not affected during exposure to fresh or acidified broth, while 4- to 12-h exposures of nonculturable cells to lysed human erythrocytes increased cellular ATP 12- to 150-fold. Incubation of nonculturable cold-starved cells with an erythrolytic lysate increased total RNA expression and ureA mRNA transcription as measured by quantitative real-time reverse transcription-PCR. Furthermore, the number of structurally intact starved coccoids containing polyphosphate granules increased almost fourfold (P = 0.0022) under the same conditions. In conclusion, a specific environmental stimulus can induce ATP, polyphosphate, and RNA metabolism in nonculturable H. pylori, indicating viability of such morphological forms.

Helicobacter pylori, a gram-negative spiral-shaped bacterium, colonizes primarily the mucosal layer of the gastric epithelium and is recognized as the main cause of gastritis and peptic ulcer disease in humans (27, 33). During infection, a majority of the H. pylori cells are present as actively dividing spiral-shaped forms (45). A morphological switch from the spiral form, possibly through a so-called U form, into a nondividing coccoid form occurs under various environmental conditions, such as aerobicosis (8), temperature changes (37), extended incubation (40), and antibiotic treatment (4, 6). A high density of coccoid forms of H. pylori has been observed in the human stomach (10), often in close association with damaged mucous cells (19).

Formation of nonculturable coccoid forms was also described for Campylobacter jejuni, some marine Vibrio species, and some other gram-negative bacteria in response to temperature changes and nutrient starvation (3, 21, 34). Coccoid forms of some of these organisms have been shown to revert into dividing organisms upon improvement of the environmental conditions (21, 34).

The coccoid form of H. pylori is not culturable in vitro, and it has been reported that this form represents the morphological manifestation of cellular degeneration and cell death (26).

However, studies of nonculturable H. pylori indicate viability of such forms (9, 15, 37, 46). In a study by West et al. (46), H. pylori was able to survive in water under certain conditions, retaining the ability to take up tritium-labeled thymidine (37). Oxidative metabolism has been observed in coccoid forms of H. pylori (9), and respiration was measured in cells starved for as long as 8 months (15). Moreover, coccoid forms of H. pylori were shown to adhere to eucaryotic cells and induce cellular changes similar to those induced by spiral forms, including tyrosine phosphorylation of specific proteins (36). Finally, BALB/cA mice orally infected with the coccoid form of H. pylori developed gastric inflammation with the same severity as animals infected with the spiral form (44).

Both an oral-oral route and a fecal-oral route seem to be involved in the transmission of infection (24, 28, 35). However, H. pylori has not been cultured from environmental specimens, from the oral cavity, or to a significant extent from feces, suggesting a role of nonculturable viable forms in disease transmission. Therefore, to understand the epidemiology of H. pylori infection, it is important to investigate the role of nonculturable cells as potential survival forms in extragastric environments. This study compared concentrations of cellular ATP, gene expression, total RNA, morphology, and cytoplasmic granules of polyphosphate (poly-P) and iron of culturable and nonculturable H. pylori cells maintained under different conditions. The metabolic response to nutrient stimulus or acid stress was analyzed to measure potential viability in suspen-
sions of nonculturable H. pylori devoid of detectable spiral forms.

**MATERIALS AND METHODS**

**Bacterial strain and culture conditions.** H. pylori strain CCUG 17874 was used throughout this study. The strain was cultured on GAB-Camp agar (39) without antibiotics for 2 days at 37°C in a microaerobic atmosphere (5% O2, 10% CO2, and 85% N2). Single colonies were inoculated into flasks containing 50 ml of a gonococcal broth (GB) (pH 7.6), originally described for culturing of *Neisseria gonorrhoeae* (38), supplemented with 5% horse serum (Gibco, Paisley, Scotland). Cultures were incubated for 30 h at 37°C on a rotary shaker (200 rpm) in anaerobic jars with a microaerobic atmosphere generated by Anaerocult C en- velopes (Merck, Darmstadt, Germany). An inoculum of 1%, corresponding to approximately 10^8 CFU of *H. pylori* per ml, was suspended in 50 ml of fresh GB and incubated as described above. The microaerobic atmosphere was generated every 24 h. Cultures were performed in triplicate. The CFU number in each culture was monitored regularly. Aliquots (10 ml) were centrifuged at 4,000 × g for 10 min, resuspended in 1 ml of phosphate-buffered saline (PBS) (pH 7.2), diluted, and seeded on agar. Single colonies were counted after 5 days of culture.

In addition, at different time points during stationary-phase culture, 5 ml was washed once in PBS and resuspended in either spent broth, fresh broth, or fresh broth containing 0.2% (vol/vol) lysed human erythrocytes. Cellular ATP, total RNA, gene expression, bacterial morphology, and poly-P granule content were subsequently determined.

**Cold starvation.** *H. pylori* cells were cold starved as described by Mizoguchi et al. (29), with the exception that GB was used for the initial culture. Aliquots (5 ml) of aging cold-starved *H. pylori* were harvested, centrifuged, and resuspended in (i) fresh broth, (ii) fresh broth adjusted to pH 5, (iii) fresh broth adjusted to pH 5 containing 5 mM urea, or (iv) fresh broth containing 0.2% (vol/vol) lysed human erythrocytes. Cellular ATP, total RNA, gene expression, bacterial morphology, and poly-P granule content were subsequently determined.

**TEM.** Fixation, staining, and embedding of *H. pylori* cells for transmission electron microscopy (TEM) were as previously described with few modifications (2). Approximately 10^8 *H. pylori* cells were washed once with 5 ml of minimal essential medium (Gibco), resuspended in 5 ml of equal volumes of minimal essential medium and 0.1 M sodium cacodylate buffer (pH 7.4) containing 3% (vol/vol) glutaraldehyde and 0.1 M sodium cacodylate buffer. Fixation in osmium and uranyl acetate was excluded. Thin sections (70 nm) were examined in an electron microscope (CM120 BioTWIN) equipped with a Gatan bio

**Cellular ATP, total RNA, gene expression, bacterial morphology, and poly-P granule content were subsequently determined.**

**RESULTS**

**H. pylori growth in broth culture and during cold starvation.** During broth cultures the highest CFU counts were obtained after 48 h. A decline of the CFU count was recorded at day 4, and no colonies (≤0.1 CFU/ml) were formed after 9 days of culture (Fig. 1A). For cold starvation experiments, 3-day broth cultures of late-exponential-phase *H. pylori* were suspended in PBS and maintained at 8°C. In contrast to broth-cultured cells, cold-starved bacteria were cultivable for an extended period of time. Eighteen days after suspension of *H. pylori* in PBS at 8°C, the cells were nonculturable (≤0.1 CFU/ml) after seeding onto GAB-Camp agar (Fig. 1B).

**Electron microscopy studies.** The majority of the spiral forms were 2 to 4 μm long and 0.5 to 0.8 μm wide (Fig. 2A) and were found in broth cultures up to day 8 (Table 1). U forms, with the cytoplasmic body inside a distended outer membrane (Fig. 2B), were observed in small numbers in all broth culture samples; however, these forms were abundant during cold starvation (Table 1). Coccolid forms of *H. pylori* were subdivided ultrastructurally into an intact (IC) or a degenerative (DC) form, depending on the size and density of the cytoplasm (Fig. 2B). The cytoplasmic body of the IC forms was 1 to 2 μm in diameter, and that of the DC forms was 3 to 4 μm in diameter (Fig. 2B). The frequencies of the IC forms were similar in 22-day broth cultures and after 45 days of cold starvation, being approximately 50% of the total cell count.
In contrast, DC forms were present in very small numbers during cold starvation (Table 1), whereas these constituted about 50% of the cells in 22-day broth cultures. Sheathed flagella, often in small bundles, were found in all preparations of H. pylori. Broth-cultured and cold-starved forms contained distinct dense cytoplasmic granules (poly-P) and crystalline inclusions, and through analysis by EFTEM at 152 and 59 eV, distinct signals corresponding to phosphate and iron, respectively, were detected (data not shown). Some poly-P granules were electron dense, while others showed sublimation characteristics, i.e., loss of the granule content during sectioning (Fig. 2A). The distributions of poly-P and iron inclusions in the different morphological forms of H. pylori are shown in Table 1.

Cytoplasmic ATP content. Trichloroacetic acid-treated cells were frozen for up to 2 weeks before the ATP assay without

![Graph A](image1.png)

![Graph B](image2.png)

**FIG. 1.** Viable counts and intracellular ATP content of H. pylori CCUG 17874 during extended culture in GB (A) or during cold starvation in PBS (B). Viable counts (○) were estimated by dilution plating (CFU per milliliter), and cellular ATP (■) was determined by bioluminescence. Error bars represent the standard deviations of the means of triplicate samples.
FIG. 2. (A) TEM of thin sections of *H. pylori* cultured in broth for 2 days. Most of these cells were spiral and contained poly-P granules showing sublimation characteristics (arrow). The inset (magnified) shows part of a cell with an intact poly-P granule (small arrow) and crystalline iron (large arrow). (B) TEM of thin sections of *H. pylori* cultured in broth for 16 days. Three different morphological types are illustrated: a U form (large arrow), IC forms (arrowheads), and DC forms (small arrows). Bars, 1 μm.
significant loss of ATP content. Interestingly, a freeze-thaw step was crucial to obtain optimal release of intracellular ATP. Organisms of 2-day broth cultures, predominantly spiral forms, contained on average 200 nM ATP. ATP successively decreased to day 12, when the content leveled out at 0.1 nM on average. Cells were then nonculturable, being predominately coccoid with occasional U forms. At day 20 the ATP content was further decreased, and at day 25 ATP was not detectable (Fig. 1A). In comparison, cold-starved \textit{H. pylori} generally retained higher concentrations of cellular ATP, with ATP concentrations decreasing less rapidly than during broth culture and being detectable during a longer period of time (Fig. 1B). Thirty-day nonculturable cold-starved cells contained on average 1.9 nM intracellular ATP, and 45-day cells contained 1.5 nM (Fig. 1B). Hence, nonculturable preparations of \textit{H. pylori}, kept at low temperature and nutritionally starved, contained more than 10-fold-higher concentrations of ATP than nonculturable \textit{H. pylori} in extended broth cultures. The ATP contents of both broth culture and cold starvation supernatants were negligible (10- to 100-fold less) compared with the intracellular ATP in all samples tested. ATP leakage was detected almost exclusively in the supernatant of cells during the first week of broth culture, while extracellular ATP was not detected in supernatants of cultures containing a majority of coccoid forms (data not shown).

### Total RNA Content
Total RNA was purified from 5 x 10^8 cells of either exponential-phase broth cultures, extended broth cultures, or cold-starved cells. Exponential-phase, 2-day broth cultures, comprising >80% spiral-shaped organisms, contained on average 123 μg of total RNA per ml. Extended broth cultures, with >95% of the organisms being of coccoid morphology and a few percent being U forms, contained 21 μg/ml after 10 days, 8.2 μg/ml after 20 days, 5.4 μg/ml after 40 days, and 4.3 μg/ml after 60 days of culture. Cold-starved cells contained 105 μg of RNA per ml after 3 months and 5.7 μg/ml after 28 months.

### Gene Expression
All RNA preparations were negative with conventional PCR if the RT reaction was omitted or if the preparations were pretreated with RNase. Conventional RT-PCR was performed on broth-cultured \textit{H. pylori} after 4, 20, 30, and 60 days and after 1, 3, and 28 months of cold starvation. Expression of the \textit{vacA} and \textit{ureA} genes, as well as the gene for a 26-kDa protein (\textit{tsaA}), was detected at all time points tested for both broth-cultured and cold-starved cells, demonstrating that these genes are expressed in nonculturable \textit{H. pylori}. The \textit{cagA} gene was expressed after 40 days but not after 60 days of broth culture and for up to 3 months of cold starvation. Expression of the \textit{ureA} gene, detected by real-time RT-PCR, was performed on broth-cultured \textit{H. pylori} after 4, 20, 40, and 60 days and after 3, and 28 months of cold starvation (Fig. 3). The \textit{CP} value, i.e., the cycle number where amplification is detected, is related to the target concentration. A low \textit{CP} value indicates an early detection of amplification, corresponding to a high concentration of target cDNA, and vice versa. Clear differences in the levels of \textit{ureA} gene expression were noted (Fig. 3A). The \textit{CP} values were approximately 30 for broth-cultured \textit{H. pylori} after 4, 20, and 40 days; 32 for broth-cultured \textit{H. pylori} after 60 days; and 21 and 30 for cold-starved \textit{H. pylori} after 3 and 28 months, respectively. The specificity of the amplification was verified by melting-curve analysis and gel electrophoresis (Fig. 3B and C).

### Response to Acid Stress and Nutrient Stimuli
(i) **Broth Culture**
Twelve-day cultures contained mainly coccoid forms and a few U-forms. After cells of 12-, 16-, and 18-day cultures were transferred to fresh broth containing lysed erythrocytes and reincubated for 12 h, the cellular ATP content increased 16-, 4-, and 2-fold in the 12-, 16-, and 18-day cultures, respectively, compared with the cellular ATP content of control cells kept in spent broth (Fig. 4A). Total RNA concentrations did not vary for 40-day cells incubated in fresh medium with or without erythrocyte lysate. In 4- to 60-day cultures RT-PCR products were amplified using primers for \textit{ureA}, \textit{vacA}, \textit{cagA}, and the gene encoding a 26-kDa protein. Nutitionally (erythrocyte lysate) stimulated cells from these cultures were also positive in RT-PCR using \textit{ureA} primers. With real-time RT-PCR using \textit{ureA} primers, no effect of erythrocyte lysate was detected on \textit{ureA} gene expression of 40-day cells (Fig. 5A).

(ii) **Cold Starvation**
The intracellular ATP content of cold-starved cells was monitored during exposure to different environmental conditions at 30 and 45 days postinoculation in PBS at 8°C. Cellular ATP was measured prior to incubation in broth with erythrocyte lysate. A low increase of cellular ATP was recorded for 30-day cells stimulated with fresh broth. A decline of the cellular ATP was detected in cells exposed to fresh broth adjusted to pH 5 or fresh broth adjusted to pH 5 containing 5 mM urea (Fig. 4B). Stimulation of 30-day cells with broth

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**TABLE 1.** Cell morphology and cytoplasmic content of iron inclusions and poly-P granules in \textit{H. pylori} during extended culture in GB (2 to 22 days) and during cold starvation in PBS (30 days to 28 months) determined by TEM

<table>
<thead>
<tr>
<th>Time</th>
<th>% of total</th>
<th>% Containing:</th>
<th>% of total</th>
<th>% Containing:</th>
<th>% of total</th>
<th>% Containing:</th>
<th>% of total</th>
<th>% Containing:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spreads</td>
<td>Fe</td>
<td>P</td>
<td>U forms</td>
<td>Fe</td>
<td>P</td>
<td>IC forms</td>
<td>Fe</td>
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<tr>
<td>2 days</td>
<td>83</td>
<td>13</td>
<td>18</td>
<td>0.5</td>
<td>16</td>
<td>2</td>
<td>11</td>
<td>0.5</td>
</tr>
<tr>
<td>5 days</td>
<td>72</td>
<td>1</td>
<td>22</td>
<td>2</td>
<td>21</td>
<td>8</td>
<td>8</td>
<td>5</td>
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<tr>
<td>8 days</td>
<td>6</td>
<td>42</td>
<td>8</td>
<td>79</td>
<td>42</td>
<td>54</td>
<td>54</td>
<td>45</td>
</tr>
<tr>
<td>22 days</td>
<td>4</td>
<td>33</td>
<td></td>
<td>60</td>
<td>38</td>
<td>4.5</td>
<td>2.5</td>
<td>1</td>
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<tr>
<td>30 days</td>
<td>37.5</td>
<td>21</td>
<td>7</td>
<td>49.5</td>
<td>35</td>
<td>27</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>45 days</td>
<td>48.5</td>
<td>20</td>
<td>22</td>
<td>71.5</td>
<td>39</td>
<td>16</td>
<td>18.5</td>
<td>20</td>
</tr>
<tr>
<td>3 mo</td>
<td>10</td>
<td>34</td>
<td>19</td>
<td>86.5</td>
<td>4</td>
<td>11</td>
<td>9</td>
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<tr>
<td>28 mo</td>
<td>4.5</td>
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\(^a\) Iron-containing inclusions.
\(^b\) Poly-P-containing granules.
containing lysed erythrocytes increased cellular ATP 150-fold within 4 h at 37°C (Fig. 4B), whereas ATP in 45-day cells increased 7- and 12-fold after 2 and 4 h, respectively (Fig. 4C). Exposure of 45-day cells to fresh broth adjusted to pH 5 with and without urea reduced the cellular ATP content in comparison with nonstimulated cells (data not shown).

The cell morphology and iron and poly-P contents of cells incubated for 12 h in fresh broth compared with nontreated (spent) organisms showed similar ultrastructural patterns (data not shown). However, after 12 h of incubation of 30-day cells with broth and erythrocyte lysate, the relative number of cells containing poly-P (46 of 274, or 16.8%) increased 3.7-fold \((P = 0.0022)\) compared with cells incubated in fresh broth (8 of 160, or 5%). Three-month cells contained 105 \(\mu\)g of total RNA per ml. Similar cells incubated with erythrocyte lysate for 4 h contained on average 188 \(\mu\)g of RNA per ml. All RNA preparations of cold-starved bacteria, except those from 28-month cells analyzed with \(cagA\) primers, were RT-PCR positive with either of the four primer sets. When 3-month cells were analyzed after 8 h of erythrocyte lysate stimulus using real-time RT-PCR, a clear increase in the urease A mRNA level was found compared with nonstimulated cells. The \(Cp\) value of stimulated cells was reduced to 22, compared with 29 for spent cells (Fig. 5A). The specificity of the amplification was verified by melting-curve analysis and gel electrophoresis (Fig. 5B and C).

**DISCUSSION**

Spiral forms of \(H. pylori\) switch to coccoid forms through intermediate C or U forms (20, 23, 32, 40). Our present find-
ings support this classification and the classification of coccoids into IC and DC forms, according to ultrastructural characteristics observed by TEM studies. The DC forms were enlarged and contained less nuclear material with diffuse characteristics. In contrast, coccoid forms with an intact outer membrane had a nuclear composition similar to that of spiral forms and showed no signs of cellular degeneration.

In this study, the culturability of *H. pylori* was highly correlated with the presence of spiral forms as observed by TEM. These results were not in accordance with a study by Kusters et al. (26) reporting that culturability was lost when approximately 50% of the *H. pylori* cells were still in the spiral form. This may be related to the use of optimized agar culture conditions. Andersen et al. (1) used a medium containing an erythrocyte lysate to culture *H. pylori*, with a morphological switch occurring at 18 h postinoculation, after 72 h of culture spherical cells devoid of urease activity regained this activity, and spiral-shaped cells appeared after transfer to fresh medium. However, it is difficult to know if a 72-h culture is completely devoid of spiral forms.

Several bacteria that transform into coccoids, such as *H. pylori*, *Salmonella*, and *Vibrio cholerae*, have homologues to poly-P kinase, which converts poly-P and ADP to ATP (25). Poly-P may be an important energy and phosphorus source also for cells during starvation, essential for endogenous metabolism, as proposed by Bode et al. (5). In this study, the presence of poly-P in all forms of *H. pylori* except DC forms correlated well with culturability and the presence of ultrastructurally intact cells. In addition, poly-P was abundant in nonculturable *H. pylori* with an ability to synthesize cellular ATP and mRNA in response to a nutrient stimulus. In *Escherichia coli*, poly-P accumulates as a result of cellular responses to deficiencies in an amino acid or nitrogen, and mutants of *E. coli* lacking poly-P kinase die after only a few days in stationary phase (25).

Iron is an essential growth factor for *H. pylori*, and the ability of tissue-invading pathogens to cause disease is generally related to iron-scavenging capacity (13). Sequence analysis indicates that *H. pylori* has such a capacity (42). In this study we showed, based on EFTEM and ultrastructural similarities, that crystalline inclusions in both spiral and coccoid forms of *H. pylori* contain iron. *H. pylori* has been found to bind human lactoferrin (13), but the lactoferrin binding capacity of the coccoid form was significantly higher than that of the spiral form (22). Intracellular crystal structures, associated with rapid growth, were described for *Bacteroides nodosus* (18). Frazier et al. (14) demonstrated such iron inclusions in *H. pylori*, and by expressing the *H. pylori* ferritin in *E. coli*, the growth rate significantly increased.

In agreement with Sörberg et al. (40), we found high levels of cellular ATP (≥10 nM) in 2- to 5-day broth cultures, while 8-day cells of nonculturable coccoid and U forms contained approximately 1 nM. After day 12 of broth culture, cellular ATP declined (to ~0.1 nM), and it was detectable up to day 23; cellular ATP was determined at 2, 4, and 8 h of stimulation.}

![FIG. 4. Effect of human erythrocyte lysate (0.2%, vol/vol) on cellular ATP content of *H. pylori*. (A) *H. pylori* was broth cultured for 12, 16, and 18 days, harvested, and transferred to either fresh broth (□) or fresh broth containing erythrocyte lysate (■). Cellular ATP was determined after subculture at 37°C for 12 h. (B) Intracellular ATP content of 30-day suspensions of cold-starved nonculturable *H. pylori* exposed to various nutrient and pH conditions. Cellular ATP was determined prior to exposure of the cells to (i) GB (B); (ii) broth containing lysed human erythrocytes (BE); (iii) broth adjusted to pH 5 (BS); or (iv) broth adjusted to pH 5 and containing 5 mM urea (BSU). Cells were analyzed after 4, 8, and 12 h of exposure to these conditions. (C) Intracellular ATP content of 45-day cold-starved nonculturable *H. pylori* exposed to fresh broth with (□) or without (■) the erythrocyte lysate. Cellular ATP was determined at 2, 4, and 8 h of stimulation. Duplicate experiments were performed twice. Means and standard deviations are indicated.](image)
however, cold-starved cells retained higher cellular levels of ATP over a prolonged period of time. Nonculturable structurally intact cells in such cultures may be biologically active although in the process of a slow cellular degeneration.

Bacterial mRNA usually has a half-life of 2 to 3 min and is rapidly degraded by enzymes in processes that regulate gene expression (7). Here, a clear loss of total RNA was observed after conversion to coccoid forms, which corresponds well to the findings of Narikawa et al. (31). However, in contrast to a complete degradation of rRNA observed in *E. coli*, it was shown by Monstein et al. (30) that coccoid *H. pylori* cells cleave rRNA in a specific pattern. Surprisingly, we found expression of mRNAs for three genes, i.e., *vacA*, *ureA*, and *tsaA*, in more than 2-year-old nonculturable cold-starved cell suspensions of *H. pylori*, comprising a majority of IC forms and few DC and U forms. Narikawa et al. (31) found mRNAs for urease A and a 26-kDa protein in bismuth- or bile salt-induced coccoids for an additional 5 days after negative cultures and suggested that this reflects residual life during cellular degradation.

In conclusion, spiral forms of *H. pylori* convert to coccoid forms through intermediate U forms. We found that nonculturable *H. pylori* cells rapidly produce ATP and synthesize *ureA* mRNA in responses to a human erythrocyte lysate stimulus. Moreover, in coccoid forms different inclusions containing iron and poly-P were accumulated, possibly representing energy stores during nutrient deprivation, suggesting that some coccoid forms of *H. pylori* could represent a survival mechanism in the human stomach or oral cavity, as well as outside the human

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**FIG. 5.** Comparison of urease A gene expression by real time RT-PCR of broth-cultured (40 days) and cold-starved (3 months) *H. pylori* prior to and after erythrocyte lysate stimulation (S). (A and B) Real-time detection (A) and melting-curve analysis (B) of amplified PCR products, using SYBR Green I and the LightCycler. (C) Agarose gel electrophoresis. Lanes 1 and 2, water control; lanes 3 and 4, 40-day cells; lanes 5 and 6, stimulated 40-day cells; lanes 7 and 8, 3-month cells; lanes 9 and 10, stimulated 3-month cells. The experiments were done in duplicate.
host. Further studies are needed to establish the possible pathophysiological role of nonculturable H. pylori.

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REFERENCES


