Salmonella Stimulate Macrophage Macropinocytosis and Persist within Spacious Phagosomes

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Summary

Light microscopic studies of phagocytosis showed that *Salmonella typhimurium* entered mouse macrophages enclosed in spacious phagosomes (SP). Viewed by time-lapse video microscopy, bone marrow–derived macrophages exposed to *S. typhimurium* displayed generalized plasma membrane ruffling and macropinocytosis. Phagosomes containing *Salmonella* were morphologically indistinguishable from macropinosomes. SP formation was observed after several methods of bacterial opsonization, although bacteria opsonized with specific IgG appeared initially in small phagosomes that later enlarged. In contrast to macropinosomes induced by growth factors, which shrink completely within 15 min, SP persisted in the cytoplasm, enlarging often by fusion with macropinosomes or other SP. A *Salmonella* strain containing a constitutive mutation in the *phoP* virulence regulatory locus (PhoP^c) induced significantly fewer SP. Similar to *Yersinia enterocolitica*, PhoP^c bacteria entered macrophages in close-fitting phagosomes, consistent with that expected for conventional receptor-mediated phagocytosis. These results suggest that formation of SP contributes to *Salmonella* survival and virulence.

Salmonellae are facultative, intracellular bacteria that cause systemic diseases including enteric (typhoid) fever, bacteremia, and gastroenteritis in humans and animals (1). Studies of the pathophysiology of human and mouse typhoid fever suggest that the ability to survive within macrophages is essential to pathogenesis (2–5). Though little is known of the mechanisms by which *Salmonella* survive after phagocytosis, they persist within membrane-bound phagosomes (6).

Recent studies indicate that bacterial gene expression essential to pathogenesis is linked with phagocytosis. The bacterial PhoQ (sensor-kinase) and PhoP (phosphorylated transcriptional activator) proteins specifically detect the macrophage vacuole environment and promote transcription of *pag* (*phoP*-activated gene)[1] genes, which promote virulence in mice and survival within macrophages (7, 8, 9). Maximal induction of *pag* transcription occurs 3–6 h after *Salmonella* phagocytosis by macrophages, coincident with acidification of the phagosome to a mean pH of 4.9 (9). Phagosomes containing *S. typhimurium* are delayed and attenuated in acidification, relative to phagosomes containing dead bacteria, and yet it is the eventual phagosome acidification that results in increased transcription of virulence (*pag*) genes (9).

The considerable delay in *pag* expression indicates that *Salmonella* face two different tasks inside the macrophage phagosome. They must detect some feature of the phagosomal environment as a signal for gene expression and also survive inside the phagosome long enough to respond to this signal with *pag* expression. One may therefore distinguish two questions: first, what features of the macrophage phagosome are detected by the PhoP/PhoQ system, and second, how does *Salmonella* survive inside the early phagosome long enough to allow delayed *pag* expression? It is this second question that we address here.

The PhoP regulon also includes approximately 15 proteins that are repressed by a *phoP* locus mutation that results in constitutive *pag* transcription (phenotype PhoP^c) (10). Some of these genes, termed *prg* (*phoP*-repressed gene) loci, are envelope proteins (11). PhoP^c *Salmonella* are also attenuated for mouse virulence and survival within macrophages (10). The delay between bacterial ingestion and *pag* expression predicts that a switch from *prg* to *pag* transcription occurs as the *Salmonella*-containing phagosome matures and acidifies. Thus, the proteins encoded by *prgs* may allow survival in the early phagosome, whereas those encoded by *pags* are required later.

We noticed during our measurements of pH that phagosomes containing bacteria were 3–6 μm in diameter (9). These

[1] *Abbreviations used in this paper:* DM10F, DMEM with 10% FCS; FD×10, fluoroscein-dextran of average molecular weight 10,000; M-CSF, macrophage-colony stimulating factor; NMS, normal mouse serum; *pag*, *phoP*-activated genes; *prg*, *phoP*-repressed genes; RB-BSA; Ringer's buffer/2% bovine serum albumin; SP, spacious phagosomes; TBS, Tris-buffered saline.

unusually large or spacious phagosomes (SP) were similar in size to macropinosomes, endocytic vesicles formed from plasma membrane ruffles that appear in response to PMA or macrophage colony-stimulating factor (M-CSF) (12, 13). Because cell surface ruffling has been implicated in *Salmonella* invasion of epithelial cells we postulated that formation of the SP in macrophages involves *Salmonella* induction of macropinocytosis (14–17). In this work, video and fluorescence microscopy have been used to examine the morphology of *S. typhimurium* entry and persistence inside macrophages.

Materials and Methods

Reagents. DMEM, FCS, penicillin/streptomycin, and Luria broth were obtained from GIBCO BRL (Gaithersburg, MD). Fluorescein-dextran of average molecular weight 10,000 (FD×10) was obtained from Molecular Probes, Inc. (Eugene, OR).

Bacterial Strains. In this study, all *Salmonella* strains except SL3261 were derived from the virulent *S. typhimurium* (14028s; American Type Culture Collection, Rockville, MD). Virulence-attenuated mutants of *S. typhimurium* used in these studies included strain CS003 Δ*phoP*Δ*purB* (8), SL3261 Δ*aroA* (18), CS022 *pho*-24 (10), CS015 *pho*P102::Tn*10d*-Cm (8), and JS41 DEL2911[(*bio-106*)*1510*(*aroG*$^-$)] (a gift of Dr. J. Slauch, University of Illinois–Urbana, Urbana, IL). Bacteria were killed by incubation at 65°C for 30 min; death was confirmed by plating for colony-forming units. *Yersinia enterocolitica* was isolated by the Clinical Microbiology laboratory of Massachusetts General Hospital. All strains were grown overnight in Luria broth at 37°C with shaking to stationary growth phase.

Macrophages and Cell Cultures. Bone marrow–derived macrophages were obtained from femurs of BALB/c and C3H/HeJ mice and cultured in DMEM with bone marrow medium (30% L cell–conditioned medium, 20% heat-inactivated FCS, and 50% DMEM) as described previously (19).

Opsonization. 2–3 × 10^6 bacteria/ml in 0.9% NaCl (normal saline; NS) was mixed with 10% normal mouse serum (NMS) and incubated for 30 min at room temperature. Bacteria were washed twice with NS before addition to macrophages. Bacteria were also opsonized by incubation in NS containing a 1:1,000 dilution of rabbit IgG antibody to *Salmonella* "0" antigen B (Fisher Scientific Co., Pittsburgh, PA). Opsonization with human recombinant mannose-binding protein (a gift of Alan B. Ezekowitz, Children's Hospital, Boston, MA) was the same as used for NMS, except 1 or 5 μg/ml of human recombinant mannose-binding protein resuspended in PBS with 10 mM $CaCl_2$ was used (20). The opsonization was presumed effective because increased numbers of opsonized bacteria were present intracellularly, as measured by gentamicin-resistant counts early after exposure of the organisms to macrophages (Table 1).

Time-Lapse Video Microscopy. BALB/c or C3H/HeJ mouse bone marrow–derived macrophages were plated at a density of 2 × 10^5/25-mm diameter cover slip and cultured overnight in DMEM with 10% FCS (DM10F) without antibiotics or growth factors. Macrophages were washed twice with Ringer's buffer/2% bovine serum albumin (RB-BSA: 155 mM NaCl, 5 mM KCl, 2 mM $CaCl_2$, 1 mM $MgCl_2$, 2 mM NaH_2PO_4, 10 mM Hepes, and 10 mM glucose, pH 7.2, + 2% BSA) warmed to 37°C. The coverslips were assembled into Sykes-Moore chambers (12). The chambers were filled with 1.9 ml of RB-BSA, sealed with a top coverslip, and placed in a temperature-controlled stage heater set at 36°C on an inverted microscope (IM-35; Carl Zeiss, Inc., Thornwood, NY). Cells were observed using a 100× lens, N.A. 1.25 with phase contrast optics, and images were collected using a Dage NC-66X video camera mounted onto the microscope. Video images were collected at one frame/s using an optical disc recorder (Panasonic), and were transferred to T-MAX 100 film (Kodak) using a Freeze Frame video recorder (Polaroid).

For most assays, coverslips were assembled on the microscope and a field containing one to four macrophages was recorded for ~2 min before adding bacteria. The recorder was stopped, the top coverslip of the chamber removed, and 1 ml of RB-BSA was removed and replaced with 1 ml of the same buffer containing bacteria. The ratio of macrophages to bacteria was 1:100. The top coverslip was replaced to continue the recording, which proceeded for 5–35 min.

Detection of SP by Fluorescence Microscopy. 5–10 × 10^4 macrophages from BALB/c or C3H/HeJ mice were plated on 12-mm glass coverslips and cultured overnight in DM10F without antibiotics. 10 bacteria/macrophage in 500 μl of DM10F containing 2 mg/ml of FD×10. After 30 min, macrophages were washed 5 times with PBS and incubated in DM10F containing 8 μg/ml gentamicin at 37°C. At different times, macrophages were washed 3 times in PBS, and fixed for 1 h in a pH 7.2 solution of 75 mM lysine-HCl, 37.5 mM sodium phosphate, 10 mM $NaIO_4$, 2% paraformaldehyde, 4.5% sucrose, and 0.25% sodium periodate (21). After fixation, macrophages were washed three times with Tris-buffered saline/sucrose (TBS; 20 mM Tris-HCl, 150 mM NaCl, pH 7.5, 4.5% sucrose) at 37°C. Coverslips were stained for 5 min at room temperature with 0.1 μg/ml DAPI diluted in TBS. The coverslips were washed 3 times with TBS/sucrose and mounted for microscopy in 90% glycerol, 10% PBS, and 1 mg/ml phenylenediamine (22).

Coverslips were viewed on a photomicroscope III (Carl Zeiss, Inc.) or a photoscope (Laborlux-12; E. Leitz, Inc., Rockleigh, NJ), using a 100× objective lens, N.A. 1.25, equipped with epifluorescence optics using fluorescein and ultra violet filter sets. Each experiment was performed on at least four separate occasions. At least 50 macrophages were examined per cover slip for the number of FD×10-labeled macropinosomes (phase-bright pinosomes containing FD×10), the total number 4',6-diamidino-2-phenylindol (DAPI)-stained bacteria, and the number of SP. SP were defined as FD×10-labeled phagosomes in which a significant volume of FD×10 surrounding the bacteria was visualized. Samples were coded for blind assay of the results.

Results

Salmonellae Stimulate Macropinocytosis and Persist in SP. Macrophages observed by time-lapse video microscopy displayed generalized plasma membrane ruffling and macropinocytosis within 2 min exposure to *S. typhimurium* (Fig. 1, *A* and *B*). Bacteria transiently contacted both ruffling and nonruffling regions of macrophage membranes, and were occasionally caught within membrane folds and ruffles and internalized (Fig. 2). The nascent phagosome was a bacterium enclosed within a 2–6-μm vacuole, morphologically indistinguishable from the macropinosomes forming nearby. Phagosomes were often large enough that bacteria could swim freely within the enclosed space (Figs. 1, *B* and *C*, and 2, *B–D*). In addition, some phagosomes enlarged by fusion with other phagosomes or with macropinosomes (Figs. 1, *B* and *C*, and 2, *A–D*). Many phagosomes remained spacious for the 35-min duration of the recording (Fig. 1), and although some shrank

Table 1. *Effect of Opsonization of S. typhimurium on SP Formation*

	SP	Bacteria	Percent bacteria in SP
Unopsonized	118	256	64
Anti-LPS IgG	178	600	55
NMS (complement)	161	359	51

S. typhimurium 14028s was opsonized with 1:1,000 dilution of IgG anti-LPS, 10% MNS or no opsonization. SP indicates the number of SP counted per 80 macrophages. Bacteria indicates the number of bacteria counted per 80 macrophages.

SP formation under different experimental conditions. SP were visualized by allowing BALB/c-derived macrophages to internalize *S. typhimurium* in the presence of fluorescein dextran (FD × 10). After 30 min of infection plus an additional 10 min of incubation in gentamicin to kill extracellular bacteria, macrophages were fixed and stained with DAPI. The SP formation, total number of bacteria within SP, and total number of bacteria per macrophage were scored in a blind test. The percentage of bacteria in SP were determined as the number of bacteria within SP divided by the total number of intracellular bacteria counted. Each experimental condition was repeated on at least three different occasions. A representative experiment is shown.

(Fig. 2), many SP continued to enlarge and fuse with macropinosomes.

In contrast, *Y. enterocolitica*, opsonized with mouse serum, bound tightly to the surface of macrophages, initiated a small ruffle adjacent to the bacterium (Fig. 3 *B*), and then entered macrophages within more tightly apposed phagosomes (Fig. 3, *A–D*). Though quantification of gentamicin-resistant colony forming units indicated that *Yersinia* were internalized as well as *S. typhimurium* (data not shown); generalized macropinocytosis was not observed. Fusion with phase-bright pinosomes was rarely observed and the occasional spacious phagosomes that formed around *Yersinia* shrank within 10 min (Fig. 3, *C* and *D*).

SP Formed Independent of Opsonization Conditions. We assayed for SP formation after various pretreatments of *S. typhimurium*. Unopsonized organisms as well as bacteria opsonized with complement containing NMS, antiserum containing anti-LPS IgG, and human recombinant mannose-binding protein (MBP) (20), all formed SP when assayed by fluorescence microscopy (Table 1).

The entry of unopsonized bacteria appeared identical to that of bacteria opsonized with complement. Though IgG-opsonized bacteria also stimulated membrane ruffling and generalized macropinocytosis, these organisms were observed

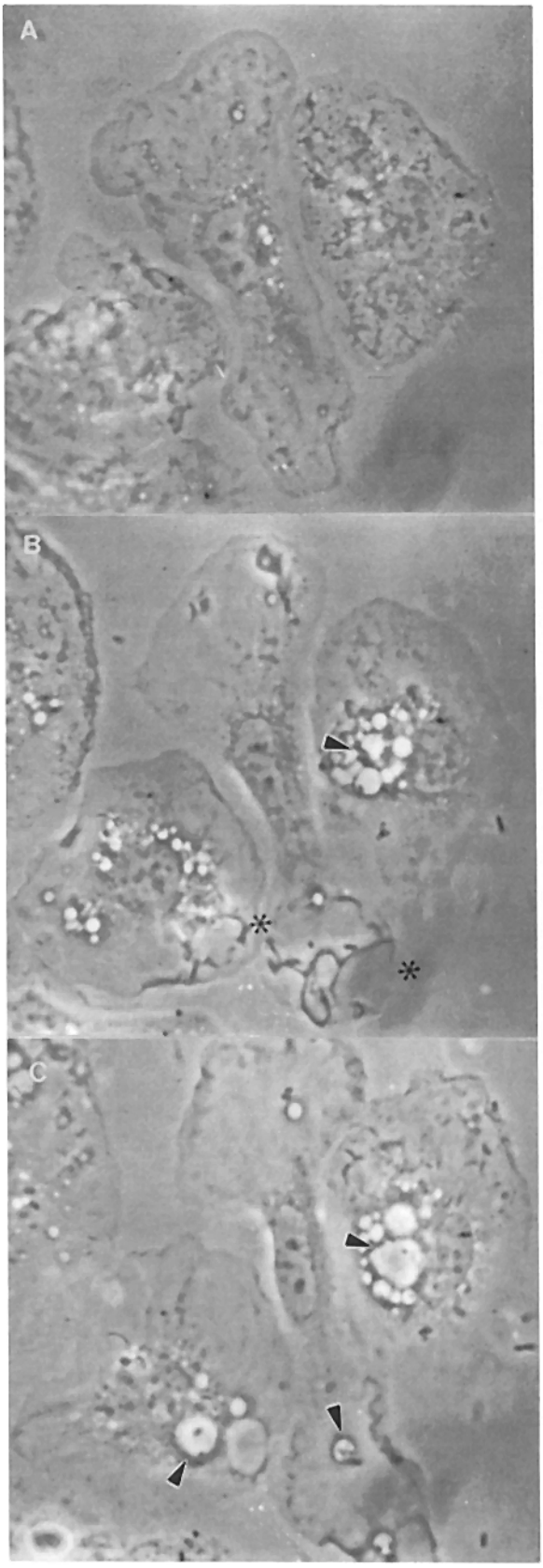

Figure 1. *S. typhimurium* stimulation of macropinocytosis and SP formation. Selected frames from a time-lapse videomicroscopy sequence of *Salmonella* phagocytosis by BALB/c bone marrow–derived macrophages. Macrophages are shown before (*A*), and 5 min (*B*) or 25 min (*C*) after infection with *S. typhimurium*. Membrane ruffling (*asterisks*) and macropinocytosis (*arrows*) began within 3 min of addition of *S. typhimurium* (*B*). Two of the SP indicated in *C*, formed from the ruffling region of the macrophage indicated by the asterisks in *B*. One SP in *C* (*uppermost arrow*) formed by fusion of smaller SP, shown in *B*.

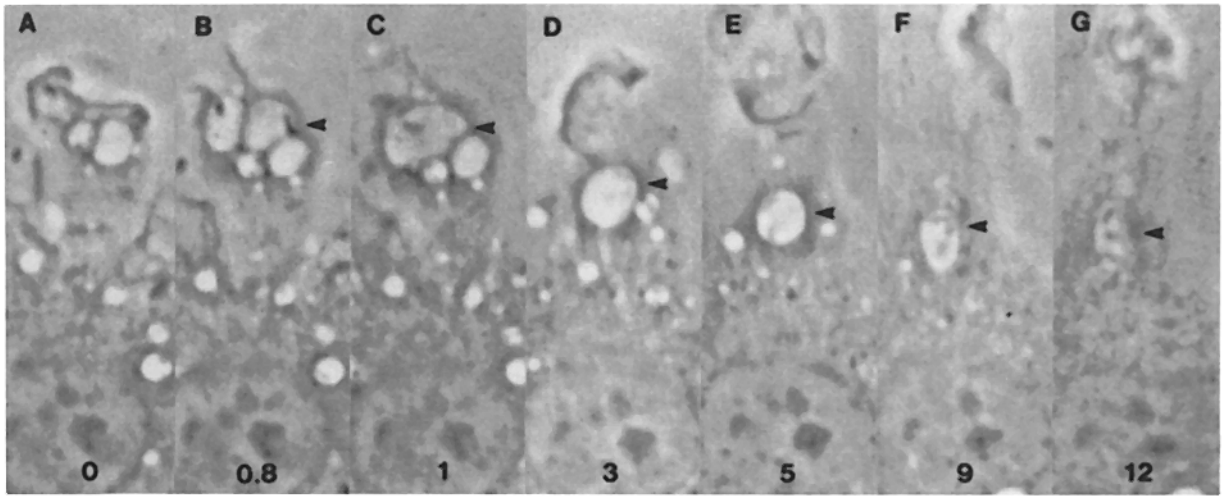

Figure 2. *S. typhimurium* phagocytosis within plasma membrane ruffles. Selected time-lapse videomicroscopic images of *S. typhimurium* phagocytosis by bone marrow–derived macrophages. *B* and *C* show a fusion event between two SP. Elapsed time in minutes is indicated at the bottom of each frame. Arrows track the progress of one SP.

to enter via smaller phagosomes (Fig. 3, *E–G*). Remarkably, during the several minutes following entry, these smaller phagosomes enlarged by fusion with macropinosomes (Fig. 3, *F–H*). The number of SP formed after 40 min of infection

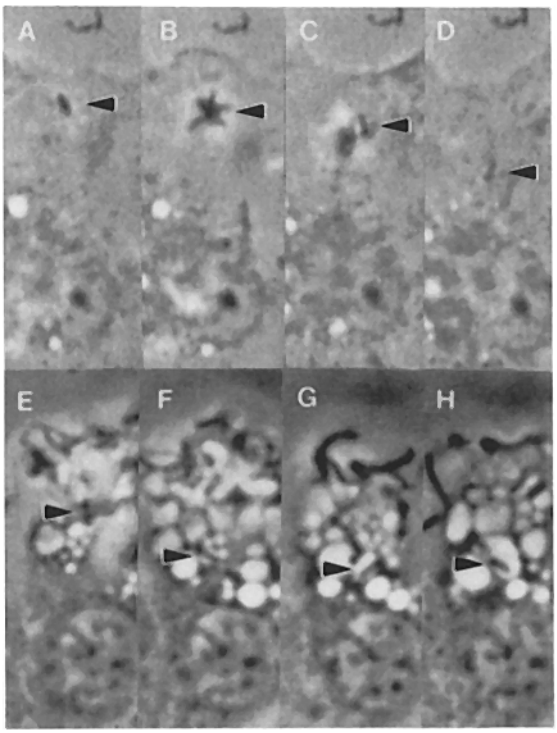

Figure 3. *Y. enterocolitica* is internalized in tightly adherent phagosomes (*A–D*). Frames are separated by 2 min. *S. typhimurium* opsonized with anti-LPS IgG entered macrophages in smaller phagosomes but form SP (*E–H*). Initially small phagosomes (*E–G*) enlarged over time (*G–H*) by fusion with macropinosomes. Frames are separated by 3.6 min. *S. typhimurium* opsonized with anti-LPS IgG also stimulated membrane ruffling and generalized macropinocytosis undistinguishable from that induced by complement-opsonized and unopsonized bacteria.

with IgG-opsonized bacteria was equal to that formed by other opsonization conditions, further indicating that phagosomes containing IgG-opsonized bacteria enlarged after formation.

The Number of SP within Macrophages Diminished Over Time. Time-lapse video microscopy indicated that SP shrank more slowly than M-CSF–induced macropinosomes, which usually become undetectably small within 10–15 min of formation (23). We therefore quantified SP and macropinosomes at different times after the addition of gentamicin to culture medium to eliminate extracellular bacteria. After 10 min, 58% of internalized bacteria were in SP and infected macrophage cultures had 15 times as many macropinosomes as macrophages infected with dead bacteria (data not shown). However, after 45 min of gentamicin treatment the percentage of bacteria in SP declined to 29%, and by 3.5 and 5.5 h after the removal of extracellular bacteria <10% of bacteria were in SP (Table 3). We have observed bacteria in SP 24 h after infection (data not shown). Thus, although most SP shrink, they do so much more slowly than macropinosomes, and some persist in the macrophage cytoplasm for many hours.

Defective Induction of Macropinocytosis and SP Formation by S. typhimurium phoP-constitutive Mutants. If SP formation is necessary for pathogenesis and intracellular survival of *Salmonella*, then some virulence-defective strains should have reduced ability to induce SP. Testing a number of strains with reduced survival within macrophages, we identified one strain deficient in SP formation and macropinocytosis (Tables 2 and 3). This strain, phenotype PhoP^c, contains a mutation in the *phoP* coordinate regulatory locus, that confers a constitutive state of *pag* expression and *prg* repression (10). All other *S. typhimurium* strains tested formed SP; including strains deleted for *phoP*, as well as purine and aromatic amino acid auxotrophs. When compared to wild type bacteria (Table 2, and Fig. 4, *A* and *B*) only PhoP^c bacteria induced significantly fewer SP (Tables 2 and 3, and Fig. 4, *C* and *D*). PhoP^c organisms formed no more macropinosomes then did

Table 2. *PhoP^c Mutants of S. typhimurium Are Deficient in Induction of SP Formation Compared with Other Avirulent S. typhimurium Strains*

Strain	Phenotype	No. SP/80 macrophages	Percent of bacteria in SP
14028s	Wild type	184	62
CS015	PhoP null	163	65
CS022	PhoP constitutive	28	15
CS003	Purine auxotroph	125	49
SL3261	Aromatic amino acid auxotroph	169	63
JS41	Rough, biotin, and aromatic amino acid auxotroph	118	45
14208s	Heat-killed	4	5

See legend to Table 1.

heat-killed bacteria, approximately eightfold fewer than that induced by wild type organisms. Consistent with the decreased formation of SP altering intracellular survival, gentamicin-resistant colony-forming units of PhoP^c bacteria were significantly reduced in the first hour after phagocytosis when compared to wild type organisms (data not shown). PhoP^c revertants isolated after selection within mice formed SP as efficiently as wild type organisms indicating that defective SP formation was correlated with this phenotype (data not shown).

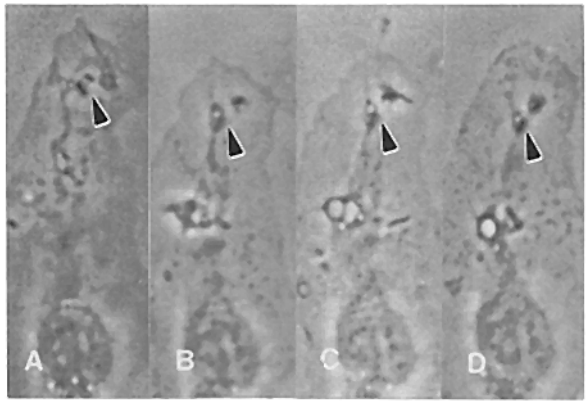

Figure 4. Video microscopy of PhoP^c *S. typhimurium* phagocytosis by macrophages. Phagocytosis by PhoP^c *S. typhimurium* was similar to phagocytosis of *Yersinia* (*A* and *B*); membrane ruffling and macropinocytosis were not stimulated. The resultant phagosomes formed are smaller and their membranes are closely opposed to the bacteria (*arrows*, *C* and *D*). Arrows indicate corresponding positions in the images. Frames are separated by 2 min.

By video microscopy, phagocytosis of PhoP^c bacteria produced smaller and more closely adherent phagosomes and showed fewer membrane ruffles and generalized macropinocytosis (Fig. 4, *A–D*). In some BALB/c but not C3H/HeJ mouse macrophages, PhoP^c bacteria-stimulated macropinocytosis and bacteria were observed in SP. However, phagocytosis of PhoP^c bacteria was always observed to be similar to *Y. enterocolitica* (Fig. 3, *A–D*). PhoP^c bacteria swam less actively than wild type *S. typhimurium*, although they exhibited normal bacterial motility when tested using a soft agar assay (data not shown). To address the possibility that PhoP^c bacteria made fewer SP because of a dose effect, macrophages were incubated with 10–100 times the normal number of bacteria,

Table 3. *SP Decreased Over Time*

Strain		Chase time 10 min	45 min	3.5 h	5.5 h
Wild type	Bacteria in SP	135 ± 2.3	65 ± 2.7	34 ± 1.4	17 ± 2
	Total number of bacteria	231 ± 1.4	228 ± 5.4	293 ± 6	358 ± 5
	Percent in SP	58	29	12	5
PhoP^c	Bacteria in SP	25 ± 1.4	8 ± 1	4 ± 1.4	0
	Total number of bacteria	136 ± 3.1	128 ± 1.4	60 ± 2.9	42 ± 1.4
	Percent in SP	18	6	7	–

30 min after infection the coverslips containing macrophages infected with *Salmonella* were washed with PBS and chased with medium containing 8 μg/ml gentamicin. The chase time indicates the time of incubation in medium containing gentamicin before infected macrophages were sampled. 80 macrophages per coverslip were analyzed. Each macrophage was quantitated for the total number of enclosed bacteria and the number of bacteria within SP. The mean and standard error of three different experiments are displayed above.

and SP formation was visualized by video microscopy. This increased the number of PhoP^c mutants internalized, but did not increase the number of macropinosomes or percentage of SP formed (data not shown). Since PhoP^c mutants are repressed in *prg* expression these results implicate *prg* products in SP formation.

Macrophage LPS Response Is Not Essential for SP Formation. *S. typhimurium* contains LPS, which can stimulate pinocytosis in macrophages derived from BALB/c but not C3H/HeJ mice, which are LPS resistant (24). To determine if *S. typhimurium* LPS was inducing macropinocytosis, *Salmonella* phagocytosis was examined in macrophages derived from C3H/HeJ mice. SP formed equally well in macrophages from these mice (data not shown). In contrast, when heat-killed bacteria were used as a source of LPS, neither SP nor macropinocytosis were induced. A *galE* mutant of *S. typhimurium*, deficient in production of the polysaccharide side chain of LPS, also formed SP as efficiently as wild-type bacteria (Table 2). The O polysaccharide side chain of LPS extracted from PhoP^c and wild type *S. typhimurium* have similar chain length (Behlau, I., and S. I. Miller, unpublished observations). These results indicated that bacterial LPS was not primarily responsible for the *S. typhimurium*–induced macropinocytosis.

Discussion

Salmonella Entry. Phagocytosis of *Salmonella typhimurium* by macrophages was unconventional both in the mechanism of entry and the morphology of the phagosome. Rather than generating a localized membrane response close to the bacterium, *Salmonella* stimulated macropinocytosis over a large portion of the macrophage surface. Bacteria that contacted the macrophage surface were sometimes caught as the membrane ruffles closed to form an intracellular vesicle. Although this would seem an inefficient mechanism of invasion, the process resulted in considerable uptake of bacteria. Uptake was enhanced by opsonization, apparently because it increased binding of bacteria to macrophages. It did not appear that more conventional mechanisms of phagocytosis were suppressed, because IgG-opsonized bacteria often entered via close-fitting phagosomes. Instead capture by already forming SP was a more rapid process than entry by conventional phagocytosis.

S. typhimurium invasion of epithelial cells also been associated with membrane ruffling (14–17). Indeed, entry into both macrophages and epithelial cells could occur by a single mechanism. However, in epithelial cells membrane ruffles are observed only in the local area adjacent to the bacterium (14, 17). In macrophages, generalized membrane ruffling and macropinocytosis of *Salmonella* was observed within minutes of exposure to bacteria and in areas without overt bacterial adherence. This suggests that a soluble factor is produced by *Salmonella* or the infected macrophage that stimulates ruffling.

Formation and Maintenance of SP. Perhaps more important than the stimulation of macropinocytosis was the formation and persistence of SP. In part, this was an obvious consequence of entry via macropinocytosis. But even close-fitting phagosomes that formed around IgG-opsonized bacteria enlarged by fusion with macropinosomes and eventually formed SP (Fig. 3, *E–H*). Unlike conventional macropinosomes, SP persisted in the cytoplasm, sometimes enlarging considerably by fusing with macropinosomes or other SP. Indeed, continued induction of macropinocytosis may be required for maintenance of SP volume.

Other mechanisms of maintaining SP volume are possible. *Salmonella* may produce molecules that inhibit the shrinkage of phagosomes that normally follows their formation. This may occur by altering macrophage transport proteins, by filling the phagosome with an osmotically active solute, or by altering the phagosome interactions with other endocytic organelles. Regarding the latter possibility, we have found that *Salmonella*-containing phagosomes merge with the lysosomal compartment, albeit somewhat slowly. The lysosomal membrane glycoprotein, lgpA, arrives in SP within 40 min of their formation, but complete delivery of the lysosomal enzyme cathepsin L to all phagosomes is delayed by ~30 min (Alpuche-Aranda, C., J. A. Swanson, and S. I. Miller, unpublished observations). It therefore appears that the SP is likely a phagolysosome, and that SP are not maintained by altering endocytic vesicle traffic.

Correlations between the PhoP Regulon and SP. One pleiotrophic *Salmonella* regulatory mutant defective in survival within macrophages was deficient in stimulating macropinocytosis and SP formation. PhoP^c bacteria were observed to enter macrophages in a fashion typical of receptor-mediated phagocytosis and to induce less macropinocytosis. This defect in SP formation was specific for PhoP^c bacteria and was not seen with several other mutants defective in virulence or survival within macrophages, including PhoP null mutants. This specificity for PhoP^c bacteria implicates *prg*-encoded proteins in the stimulation of macropinocytosis and SP formation. Because PhoP^c bacteria are attenuated for survival within macrophages this result also suggests that SP formation may be necessary for *Salmonella* survival. Most likely it is survival within early phagosomes that is enhanced by SP formation. *Salmonella* entry or SP formation may depend on expression of *prg*, and in a later phase, shrinkage and acidification of SP <5.0 results in a switch to *pag* expression. Consistent with this model, the timing of *pag* expression correlated with a significant reduction in the number of SP. In addition, PhoP^c mutants, are defective in survival early after phagocytosis while PhoP null mutants begin to show a defect only 4–6 h after macrophage infection.

The PhoP^c strain has another remarkable property in that it is highly immunogenic when used as a live vaccine (10). As few as 15 organisms provide protection against 5 logs greater wild type bacteria. Lacking further data, one can only speculate that this immunogenicity results from a deficiency in SP formation. Indeed, the normal delay in *pag* expression may allow *Salmonella* time to reach or create an intracellular compartment removed from the organelle traffic normally involved in antigen presentation.

Role of the SP in Pathogenesis. How could SP formation protect bacteria from killing by macrophages? First, the macrophage's ability to kill ingested organisms may require a close-

fitting phagosome, and a small lumenal volume, in order to obtain sufficiently high concentrations of toxic compounds. The SP could dilute such compounds, thus allowing *Salmonella* to initially survive. When combined with delay in acidification of this phagosome (9), the bacterium may create a tolerable intracellular environment. Second, a gradual exposure to an acidic environment may allow the organism time to express other genes necessary for survival.

Abshire and Neidhardt (25) have recently identified two *Salmonella* populations that exist within macrophages: one static and another replicating. Because macrophages often show a mixture of tight and spacious phagosomes, SP may contain the replicating population of *Salmonella*.

Our results indicate that some SP shrink while others are maintained for hours. How can we explain the heterogenity of SP persistance given genetic identity among the bacteria? One possibility is that survival is a cooperative enterprise. Extracellular bacteria may stimulate generalized macropinocytosis and maintain intracellular bacteria within SP. Persistance would then be modulated by initial SP size and subsequent organelle fusion events with variations in the number of extracellular bacteria affecting SP size. If the ability of SP to fuse with other SP or macropinosomes is a random event, then the more macropinosomes formed the greater the chance for organelle fusions and SP persistence.

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References

1. Hornick, R.B. 1992. Typhoid fever. *In* Infectious Diseases. S.L. Gorbach, J.G. Bartlett, and N.R. Blacklow, editors. W.B. Saunders Co., Philadelphia. 585–589.
2. Jenkin, C.R., and B. Benacerraf. 1960. In vitro studies of the interaction between mouse peritoneal macrophages and strains of *Salmonella* and *E. coli*. *J. Exp. Med.* 112:403.
3. Hornick, R.B., S.E. Greisman, T.E. Woodward, H.L. DuPont, A.T. Dawkins, and M.J. Snyder. 1970. Typhoid fever: pathogenesis and immunological control. *N. Engl. J. Med.* 283:686.
4. Carter, P.B., and F.M. Collins. 1974. The route of enteric infection in normal mice. *J. Exp. Med.* 139:1189.
5. Fields, P.I., R.V. Swanson, C.G. Haidaris, and F. Heffron. 1986. Mutants of *Salmonella typhimurium* that cannot survive within the macrophage are avirulent. *Proc. Natl. Acad. Sci. USA.* 83: 5189.
6. Carrol, M.E.W., P.S. Jackett, B.R. Aber, and D.B. Lowrie. 1979. Phagolysosome formation, cyclic adenosine 3′:5′-monophosphate and the fate of *Salmonella typhimurium* within mouse peritoneal macrophages. *J. Gen. Microbiol.* 110:421.
7. Fields, P.I., E.A. Groisman, and F. Heffron. 1989. A *Salmonella* locus that controls resistance to microbicidal proteins from phagocytic cells. *Science (Wash. DC).* 243:1059.
8. Miller, S.I., A.M. Kukral, and J.J. Mekalonos. 1989. A two-component regulatory system (*phoP/phoQ*) controls *Salmonella typhimurium* virulence. *Proc. Natl. Acad. Sci. USA.* 86:5054.
9. Alpuche-Aranda, C.M., J.A. Swanson, W.P. Loomis, and S.I. Miller. 1992. *Salmonella typhimurium* activates virulence gene transcription within acidified macrophage phagosomes. *Proc. Natl. Acad. Sci. USA.* 89:10079.
10. Miller, S.I., and J.J. Mekalanos. 1990. Constitutive expression of the PhoP regulon attenuates *Salmonella* virulence and survival within macrophages. *J. Bacteriol.* 172:2485.
11. Behlau, I., and S.I. Miller. 1993. A PhoP-repressed gene promotes *Salmonella typhimurium* invasion of epithelial cells. *J. Bacteriol.* 175:4475.
12. Racoosin, E.L., and J.A. Swanson. 1992. M-CSF-induced macropinocytosis increases solute endocytosis but not receptor mediated endocytosis. *J. Cell Sci.* 102:867.
13. Swanson, J.A. 1989. Phorbol esters stimulate macropinocytosis and solute flow through macrophages. *J. Cell Sci.* 94:135.
14. Takeuchi, A. 1967. Electron microscopic studies of experimental *Salmonella* infection I. Penetration into the intestinal epithelium by *Salmonella typhimurium*. *Am. J. Pathol.* 50:109.
15. Francis, C.L., M.N. Starnbach, and S. Falkow. 1992. Morphological and cytoskeletal changes in epithelial cells occur immediately upon interaction with *Salmonella typhimurium* grown under low-oxygen conditions. *Mol. Microbiol.* 6:3077.
16. Finley, B.B., and S. Ruschkowiscki. 1991. Cytoskeletal rearrangements accompanying *Salmonella* entry into epithelial cells. *J. Cell Sci.* 99:283.
17. Francis, C.L., T.A. Ryan, B.D. Jones, S.J. Smith, and S. Falkow. 1993. Ruffles induced by *Salmonella* and other stimuli direct macropinocytosis of bacteria. *Nature (Lond.).* 364:639.
18. Hoiseth, S.K., and B.A.D. Stocker. 1981. Aromatic-dependent *Salmonella typhimurium* are non-virulent and effective as live vaccines. *Nature (Lond.).* 291:238.

19. Racoosin, E.L., and J.A. Swanson. 1989. Macrophage colony-stimulating factor (rM-CSF) stimulates pinocytosis in bone marrow-derived macrophages. *J. Exp. Med.* 170:1635.
20. Kuhlman, M., K. Joiner, and R.A.B. Ezekowitz. 1989. The human mannose-binding protein function as an opsonin. *J. Exp. Med.* 169:1733.
21. McLean, I.W., and P.K. Nakane. 1974. Periodate-lysine-paraformaldehyde fixative. A new fixative for immunoelectron microscopy. *J. Histochem. Cytochem.* 22:1077.
22. Swanson, J.A., A.B. Bushnell, and S.C. Silverstein. 1987. Tubular lysosome morphology and distribution within macrophages depend on the integrity of cytoplasmic microtubules. *Proc. Natl. Acad. Sci. USA.* 84:1921.
23. Racoosin, E.L., and J.A. Swanson. 1993. Macropinosome maturation and fusion with tubular lysosomes in macrophages. *J. Cell Biol.* 121:1011.
24. Knight, K.R., G. Vairo, and J.A. Hamilton. 1992. Regulation of pinocytosis in murine macrophages by colony stimulating factors and other agents. *J. Leukocyte Biol.* 51:350.
25. Abshire, K.Z., and F.C. Neidhardt. 1993. Growth rate paradox of *Salmonella typhimurium* within host macrophages. *J. Bacteriol.* 175:3744.