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Matthew J. Novotny  
West Virginia University

Dacie R. Bridge  
West Virginia University

Karen H. Martin  
West Virginia University

Scott A. Weed  
West Virginia University

Robert B. Wysolmerski  
West Virginia University

See next page for additional authors

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Metastatic MTLn3 and non-metastatic MTC adenocarcinoma cells can be differentiated by Pseudomonas aeruginosa

Matthew J. Novotny1,*, Dacie R. Bridge1,*,1, Karen H. Martin1,2,3, Scott A. Weed2,3, Robert B. Wysolmerski2,3 and Joan C. Olson1,6

1Department of Microbiology, Immunology and Cell Biology, West Virginia University Health Sciences Center, Morgantown, WV 26506-9177, USA
2Department of Neurobiology and Anatomy, West Virginia University Health Sciences Center, Morgantown, WV 26506-9128, USA
3Mary Babb Randolph Cancer Center, West Virginia University Health Sciences Center, Morgantown, WV 26506-9300, USA

*These authors contributed equally to this work
1Present address: Department of Microbiology and Immunology, Uniformed Services University of the Health Sciences, Bethesda, MD 20814, USA
6Author for correspondence (Joan Olson@wvu.edu)

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Summary

Cancer patients are known to be highly susceptible to Pseudomonas aeruginosa (Pa) infection, but it remains unknown whether alterations at the tumor cell level can contribute to infection. This study explored how cellular changes associated with tumor metastasis influence Pa infection using highly metastatic MTLn3 cells and non-metastatic MTC cells as cell culture models. MTLn3 cells were found to be more sensitive to Pa infection than MTC cells based on increased translocation of the type III secretion effector, ExoS, into MTLn3 cells. Subsequent studies found that higher levels of ExoS translocation into MTLn3 cells related to Pa entry and secretion of ExoS within MTLn3 cells, rather than conventional ExoS translocation by external Pa. ExoS includes both Rho GTPase activating protein (GAP) and ADP-ribosyltransferase (ADPRT) enzyme activities, and differences in MTLn3 and MTC cell responsiveness to ExoS were found to relate to the targeting of ExoS-GAP activity to Rho GTPases. MTLn3 cell migration is mediated by RhoA activation at the leading edge, and inhibition of RhoA activity decreased ExoS translocation into MTLn3 cells to levels similar to those of MTC cells. The ability of Pa to be internalized and transfer ExoS more efficiently in association with Rho activation during tumor metastasis confirms that alterations in cell migration that occur in conjunction with tumor metastasis contribute to Pa infection in cancer patients. This study also raises the possibility that Pa might serve as a biological tool for dissecting or detecting cellular alterations associated with tumor metastasis.

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Key words: Tumor metastasis, MTC and MTLn3 cells, Pseudomonas aeruginosa, Rho GTPase, Cell migration

Introduction

The relationship between bacterial infections and cancer is complex. Bacteria, such as Helicobacter pylori, are a proven carcinogen in the development of gastric cancer and mucosa-associated lymphoid tissue lymphoma (Crowe, 2005; Montalban et al., 2001). Other bacteria, such as Salmonella typhi, Streptococcus bovis and Chlamydia pneunomea have been linked to the induction of specific types of cancers in association with chronic infection, inflammation or immune suppressive mechanisms (Dutta et al., 2000; Gold et al., 2004; Koyi et al., 2001; Kuper et al., 2000). Bacteria and their toxins have also been used to treat cancer. Coley’s vaccine, comprised of live or heat-killed Streptococcus pyogenes and Serratia marcescens, was historically used to limit many forms of cancers, presumably by engaging an immune response that protected against tumors (McCarthy, 2006). More recently, modified bacteria, bacterial toxins and re-engineered immunotoxins that target tumors or tumor-specific antigens have been used clinically to preferentially kill tumor-associated cells (Patyar et al., 2010). In addition to the role of bacteria in tumor induction or treatment, physical and immunological compromises associated with cancer or cancer treatments make cancer patients highly susceptible to bacterial infection (Benharroch and Osyntsov, 2012). Relationships between bacterial infection and tumor induction introduce the notion that there might be commonalities in mechanisms of bacterial pathogenesis and tumor induction that can be applied to an understanding of neoplastic processes.

Pseudomonas aeruginosa (Pa) is a Gram-negative, predominantly extracellular, opportunistic pathogen that frequently infects cancer patients. Pa maintains a broad range of virulence factors that contribute to its pathogenicity, but among these, the type III secretion (T3S) system is recognized to be integral to the initiation of Pa infection and is associated with...
poor clinical outcomes (Hauser, 2009). The T3S system is a needle-like nanostructure made by many Gram-negative bacteria that allows the direct translocation of proteins or ‘effectors’ from the bacterial cytosol to the host cell surface (Cornelis, 2010). T3S effectors are then internalized into host cells through a bacterially formed ‘translocon’ channel in eukaryotic cell membranes. Within the cell, T3S effectors manipulate host cell function in a bacterial specific manner to facilitate bacterial growth and survival. The importance of T3S in the establishment of Pa infection is supported by the findings that immunity induced against the T3S translocon protein, PcrV, protects against Pa infection, and that cellular susceptibility to Pa infection parallels cellular sensitivity to T3S (Bridge et al., 2010; McGuffie et al., 1999; Rucks and Olson, 2005; Sawa et al., 1999).

Pa utilizes T3S to disrupt normal host cell function and promote infection through four identified effectors, ExoS, ExoT, ExoU and ExoY. ExoS and ExoT are homologous, bifunctional proteins that include Rho GTPase activating protein (GAP) and ADP-ribose transferase (ADPRT) activities (Goehring et al., 1999; Iglewski et al., 1978; Krall et al., 2000; Yahr et al., 1996). The GAP activity of ExoS and ExoT functions in a similar manner to inhibit host cell Rho family GTPase activity and alter actin dynamics to prevent Pa internalization (Garrity-Ryan et al., 2000). ExoU plays a more pronounced role in Pa pathogenesis than ExoT (Shaver and Hauser, 2004), and this coincides with ExoS-ADPRT activity having specificity for multiple cellular proteins, including certain Ras family proteins (McGuffie et al., 1998; Fraylick et al., 2002b; Henrikkson et al., 2002), ERM (ezrin, moesin and radixin) proteins (Maresso et al., 2004; McGuffie et al., 1998), vimentin (Coburn et al., 1989), and cyclophilin A (DiNovo et al., 2006). The substrate specificity of ExoT-ADPRT activity in comparison is limited to Crk proteins (Sun and Barbieri, 2003). ExoU has phospholipase A2 activity that causes cell lysis and is associated with the most virulent Pa infections (Sato et al., 2003; Shaver and Hauser, 2004). ExoY has adenylyl cyclase activity and appears to play a limited role in Pa pathogenesis (Vance et al., 2005; Yahr et al., 1998). Translocation of T3S effectors across host cell membranes is the least understood stage in T3S but is known to require three proteins in Pa: membrane channel forming PopB and PopD and channel assembling PcrV (Mueller et al., 2008).

Examination of eukaryotic cell properties that influence T3S translocation and responsiveness to ExoS found that most cell lines were sensitive to ExoS toxicity, but different degrees of toxicity were observed (McGuffie et al., 1999; Rucks et al., 2003). Two cell lines, polarized confluent epithelial cells and undifferentiated HL-60 promyelocytic cells, have been identified to be resistant to Pa-T3S and ExoS toxicity (McGuffie et al., 1999; Rucks et al., 2003; Rucks and Olson, 2005). Notably, tumor-derived cell lines are generally highly sensitive to ExoS toxicity (McGuffie et al., 1999). More recent studies of human HT-29 colon and T24 bladder carcinoma cell lines identified a relationship between the leading edge of migrating epithelial cells and sensitivity to Pa-T3S and infection (Bridge et al., 2012; Bridge et al., 2010). The finding that carcinoma derived cell lines are highly sensitive to Pa-T3S and ExoS toxicity, while healthy polarized epithelial monolayers are resistant to both, introduces the possibility that responsiveness to ExoS toxicity might provide insight into mechanistic properties linked to carcinogenesis.

The purpose of this study was to characterize properties of carcinogenic cells that contribute to their increased sensitivity to T3S translocated ExoS and the establishment of Pa infection. Realizing the complexity of tumor development, this study focused on two closely related tumor cell lines, MTC and MTLn3 cells. These cell lines were derived from subcutaneous implantation of the rat mammary 13762 adenocarcinoma cell line into Fisher 344 rats (Neri et al., 1982), but differ in that MTC cells are non-metastatic and MTLn3 cells acquired high metastatic potential. Based on the premise that cell migration influences sensitivity to Pa infection, we examined whether alterations in cell migration associated with tumor metastasis might be a factor in influencing susceptibility to Pa infection.

Our studies found that ExoS was translocated more efficiently into highly metastatic MTLn3 cells as compared to non-metastatic MTC cells, consistent with tumor metastasis enhancing sensitivity to Pa infection. When the mechanism underlying differences in ExoS translocation between the two cell lines was examined, increased ExoS translocation into MTLn3 cells occurred in conjunction with increased Pa entry and secretion of ExoS within MTLn3 cells. Rho activation is increased at the leading edge of MTLn3 cells (El-Sibai et al., 2007; El-Sibai et al., 2008), and inhibition of Rho activity in MTLn3 cells decreased ExoS translocation to levels similar to that of MTC cells. These are the first studies to demonstrate that Rho activation in metastatic MTLn3 cells alters sensitivity to Pa infection and mechanistically link alterations in cell migration associated with tumor metastasis to increased sensitivity to Pa infection.

**Results**

Highly metastatic MTLn3 cells allow greater Pa-T3S translocation than non-metastatic MTC cells

To examine if tumor metastasis influenced sensitivity to Pa infection, we compared the efficiency of Pa-T3S translocation into non-metastatic MTC cells with that of highly metastatic MTLn3 cells. Detection of Pa-T3S translocation into eukaryotic cells requires a 1.5 to 3.5 hr co-culture period, depending on the cell line and the method of analysis (Bridge et al., 2012; Bridge et al., 2010). To adapt Pa co-culture conditions to studies of MTC and MTLn3 cells, indicated infections were performed in medium containing 5% FBS (steady state conditions) to allow cells to move randomly during the co-culture period. Examination of MTC and MTLn3 cell morphology under steady state conditions found MTC cells to have an elongated polarized morphology and a well-developed leading edge, typical of mesenchymal migration (Fig. 1A). MTLn3 cells in comparison were more rounded, lacked head-to-tail polarity, and had a broad thin lamellar region demarcated by actin. These morphological findings are similar to those previously observed for MTC or MTLn3 cells following starvation and stimulation with 5% serum (Shestakova et al., 1999), and document that metastatic properties of MTC and MTLn3 cells correspond with different migratory phenotypes.

To compare Pa-T3S translocation in MTC and MTLn3 cells, sub-confluent monolayers were co-cultured with strain PA103 AUT expressing plasmid encoded HA-tagged wild type ExoS (Pa ExoS-WT) for increasing times (0, 1.5 or 3 hr). T3S translocation was assayed by monitoring ExoS effector transfer into MTC or MTLn3 cell membrane fractions based on immunoblot analysis, which was then quantified by densitometry. As shown in Fig. 1B, no ExoS translocation was detected in uninfected (0) cells or in either cell line after co-
culture with *P. aeruginosa* ExoS-WT for 1.5 hr. Following a 3 hr co-culture period, ExoS translocation was detected in both cell lines, but significantly (*P*<0.001) higher levels of ExoS translocation (4-fold) were detected in MTLn3 cells as compared to MTC cells (Fig. 1C). ExoS immunoblots were also probed for RalA, which served as a membrane fraction loading control and is a substrate of ExoS-ADPRT activity. RalA can be ADP-ribosylated by *P. aeruginosa* ExoS-WT at two to three sites, with Arg52 functioning as a preferred site of ExoS ADP-ribosylation, and Arg135 and Arg161 functioning as secondary sites of ADP-ribosylation (Fraylick et al., 2002a). ADP-ribosylation by ExoS causes RalA to shift in mobility in a manner dependent on the number of sites of ADP-ribosylation (Bridge et al., 2012; Fraylick et al., 2002a), and the different shift in RalA mobility detected between MTC and MTLn3 cells (Fig. 1B, noted by asterisks) can be explained by RalA being ADP-ribosylated at more sites in MTC cells.

To assess if MTLn3 cells had enhanced *Pa*-T3S translocation in general, duplicate immunoblots were probed for the T3S translocin protein, PopB. Similar to ExoS, significantly (*P*<0.05) more PopB was detected in the membrane fraction of MTLn3 as compared to MTC cells after a 3 hr co-culture period (Fig. 1B,C). Both cell lines remained >90% viable following co-culture with *Pa* ExoS-WT, indicating that differences in T3S translocation did not relate to *ExoS* cytotoxicity. T3S translocation is dependent on *Pa* contact with eukaryotic cells, but differences in T3S translocation did not relate to more efficient *Pa* binding to MTLn3 cells, as an approximately equal number of *Pa* (3.5±1.3 and 3.6±1.2) bound per MTLn3 and MTC cell, respectively. Collectively these studies found that T3S translocation was more efficient in metastatic MTLn3 cells than non-metastatic MTC cells, and provided evidence that ExoS ADP-ribosylation of RalA differed between the two cell lines.

**Use of ExoS enzyme activity to characterize mechanisms underlying differences in T3S translocation in MTC and MTLn3 cells**

ExoS is a bi-functional T3S effector having N-terminal GAP activity, defined by arginine residue 146 (R146), and C-terminal ADPRT activity, defined by glutamic acid residues 379 and 381 (E379 and E381) (reviewed by Barbieri and Sun, 2004). Both activities can alter ExoS translocation into eukaryotic cells (Aili et al., 2008; Bridge et al., 2012; Cisz et al., 2008; Fraylick et al., 2001). In turn, inactivation of ExoS-GAP or ADPRT activity has proven useful in dissecting cellular mechanisms that underlie T3S translocation and *Pa* infection (Bridge et al., 2012). To determine if mutations that inactivate ExoS-GAP or ADPRT activities might provide insight into mechanisms underlying increased *Pa*-T3S translocation into metastatic MTLn3 cells, MTC and MTLn3 cells were co-cultured for 3 hr with strain PA103ΔUT expressing plasmid encoded ExoS-HA with an R146A mutation, ExoS-GAP(–), or E379A and E381A mutations, ExoS-ADPRT(–). T3S translocation was assayed based on ExoS and PopB transfer into membrane fractions by immunoblot analysis, and this was compared with translocation of *Pa* ExoS-WT, a *Pa* pUCP vector control, and uninfected cells.

As represented in Fig. 2A and quantified in 2B, inactivation of ExoS-GAP activity significantly enhanced ExoS translocation into both cell lines, as compared to *Pa* ExoS-WT, and allowed ExoS translocation into MTC cells to closely approximate that of MTLn3 cells. Inactivation of ExoS-ADPRT activity also caused a modest, but significant (*P*<0.01) increase in ExoS translocation into MTC cells when compared to *Pa* ExoS-WT (not noted in Fig. 2B). The increase in ExoS translocation into MTLn3 cells caused by inactivation of ExoS-ADPRT activity did not gain statistical significance when compared to *Pa* ExoS-WT. Comparisons between MTC and MTLn3 cells confirmed a significant increase in translocation of ExoS-WT (*P*<0.001) and ExoS-ADPRT(–) (*P*<0.01) into MTLn3 as compared to translocation of the respective effectors in MTC cells. No significant difference in ExoS-GAP(–) translocation was detected between the two cell lines. Alterations in PopB
translocation caused by inactivation of ExoS-GAP or ADPRT activity generally paralleled alterations in ExoS translocation but were less pronounced and did not gain statistical significance (Fig. 2C). The Pa pUCP vector control included in this study maintains a functional T3S system but lacks T3S effectors. Consistent with these properties, PopB but not ExoS translocation was detected following co-culture with Pa pUCP. As in Fig. 1, alterations in ExoS translocation did not relate to cytotoxic effects of Pa strains, and differences in the efficiency of ExoS ADP-ribosylation of RalA were still evident between the two cell lines (Fig. 2A).

The most important findings of these analyses were that: 1) ExoS-GAP activity, and to lesser extent ExoS-ADPRT activity interfered with ExoS translocation into MTC and MTLn3 cells, indicating that ExoS was able to modulate T3S translocation by two independent mechanisms. 2) Inactivation of ExoS-GAP activity nullified differences in ExoS translocation between MTC and MTLn3 cells, indicating that differences in ExoS translocation between the two cell lines related to their reactivity to ExoS-GAP activity. This led to our examining whether ExoS-GAP activity might serve as a tool to further characterize cellular differences that contribute to metastatic properties of MTLn3 cells.

ExoS-GAP activity differentially alters MTC and MTLn3 cell morphology

Effects of ExoS-GAP activity on MTC and MTLn3 cell function were further examined by immunofluorescence microscopy (IF), following co-culture with Pa expressing ExoS with active GAP, Pa ExoS-WT or Pa ExoS-ADPRT(−). and compared with alterations induced by Pa ExoS-GAP(−). MTC or MTLn3 cell morphology was examined after a 1 hr 45 min co-culture period, which was previously found to allow detection of low levels of ExoS translocation by IF, while limiting toxic effects of ExoS on cell morphology (Bridge et al., 2012). Following co-culture, cells were stained for extracellular or intracellular Pa, HA to detect ExoS effector translocation, and actin to detect alterations in cytoskeletal structure.

Distinctly different alterations in MTC and MTLn3 cell morphology were observed following co-culture with Pa expressing ExoS-WT (Fig. 3A,B, ExoS-WT panels). Translocation of ExoS-WT caused MTC cells to contract and leading edge architecture was replaced with branched actin filaments that remained adherent to cell matrix. Translocation of ExoS-WT into MTLn3 cells caused loss of actin demarcation of the lamellipodium, and instead actin-spiked projections protruded from within the lamellipodium. Pa expressing ExoS-WT was also internalized more efficiently into MTLn3 cells than MTC cells. Consistent with Pa ExoS-WT and Pa ExoS-ADPRT(−) both having GAP activity, morphological alterations caused by these two strains were similar. As with Pa ExoS-WT, Pa ExoS-ADPRT(−) caused MTC cells to contract, while branched actin filaments remained adherent cell matrix (Fig. 3A, ExoS-ADPRT(−) panels). In MTLn3 cells, Pa ExoS-ADPRT(−) caused actin-spiked projections to protrude from within the lamellipodium, similar to that observed in response to Pa ExoS-WT (Fig. 3B, ExoS-ADPRT(−) panels).

Inactivation of ExoS-GAP activity led to somewhat similar morphological outcomes in MTC and MTLn3 cells. Long, non-branched actin filaments projected from the lamellipodium of MTC cells in response to Pa ExoS-GAP(−), while the cells retained their same general morphological shape (Fig. 3A, ExoS-GAP(−) panels). Long actin filaments were also observed to project from the lamellipodium of MTLn3 cells in response to Pa ExoS-GAP(−), but the leading edge of MTLn3 cells often became distorted, as observed in Fig. 3B, ExoS-GAP(−) panels. Inactivation of ExoS-GAP increased Pa internalization into both MTC and MTLn3 cells, and this was accompanied by detection of ExoS-GAP(−) effector secretion by internalized Pa in both cell lines (Fig. 3A,B, enlarged ExoS-GAP(−) panels, marked by
blue arrows). In summary, MTC and MTLn3 cells responded differently to \( Pa \) when ExoS-GAP was active but produced similar morphological outcomes when ExoS-GAP was inactive. The most severe morphological alterations caused by ExoS-GAP in both cell lines were alterations in actin organization affecting leading edge or lamellipodium architecture. These results are consistent with ExoS-GAP activity responding to differences in migratory properties of non-metastatic MTC and metastatic MTLn3 cells.

**Metastatic properties of MTLn3 cells enhance \( Pa \) internalization**

The observation that \( Pa \) internalization was enhanced in association with increased ExoS translocation into MTLn3 cells led to our examination of the relationship between \( Pa \) internalization and ExoS translocation. \( Pa \) internalization into MTC or MTLn3 cells was visually enumerated, using IF staining and microscopy to identify intracellular \( Pa \), in four independent experiments, where co-culture times ranged from 1 hr 45 min to 3 hr (Fig. 4A). Fig. 4B is included to allow direct comparisons of ExoS translocation based on immunoblot analysis with \( Pa \) internalization. \( Pa \) expressing ExoS-WT were internalized into MTLn3 cells 5-fold more efficiently than into MTC cells \((P<0.01)\), and this corresponded with a 4.4-fold increase in ExoS-WT translocation into MTLn3 cells than MTC cells. When ExoS-GAP activity was inactivated, \( Pa \) internalization increased 20-fold \((P<0.001)\) in MTC cells and 4-fold in MTLn3 cells \((P<0.01)\), when compared to \( Pa \) ExoS-WT, essentially eliminating differences in \( Pa \) internalization between the two cell lines (Fig. 4A). No significant differences in \( Pa \) internalization were observed in either cell line between \( Pa \) ExoS-WT and \( Pa \) ExoS-ADPRT \((-)\); collectively, when \( Pa \) internalization and ExoS translocation were compared in MTC and MTLn3 cells following treatment with \( Pa \) ExoS-WT, \( Pa \) ExoS-GAP \((-)\) or \( Pa \) ExoS-ADPRT \((-)\) (comparisons of data represented in Fig. 4A,B) a positive \((r=0.96)\) correlation was observed, indicating that the efficiency of ExoS transfer into MTC and MTLn3 cells directly correlated with the efficiency of \( Pa \) internalization.

IF analysis of ExoS translocation into MTC and MTLn3 cells following a 3 hr co-culture found ExoS effector staining to be more intense in both cell lines (Fig. 4C,D), as compared to a 1 hr 45 min co-culture time in Fig. 3. Cells in general also became more rounded after the longer co-culture time. In MTC cells effector staining was observed to align with branched actin filaments that remained adherent to the cell matrix as cells contracted in response to \( Pa \) ExoS-WT or \( Pa \) ExoS-ADPRT \((-)\) (Fig. 4C, insets show enlargement of ExoS-WT and ExoS-ADPRT \((-)\) effector alignment with actin). Alignment of ExoS-WT or ExoS-ADPRT \((-)\) effector with actin was not evident in MTLn3 cells, rather effector was diffusely distributed within the cell. Consistent with immunoblot analysis (Fig. 2A) effector staining reached highest intensity in both MTC and MTLn3 cells following co-culture with \( Pa \) ExoS-GAP \((-)\) and was both diffuse within the cell and in close association with internalized \( Pa \).
increased translocation in MTC and MTLn3 cells in conjunction with and that inactivation of ExoS-GAP equilibrates ExoS relates to evidence that increased ExoS translocation into MTLn3 cells opportunity to gain access to membrane associated RalA during ADP-ribosylation of RalA in MTC cells, as ExoS would have an external WT is predominately T3S translocated into MTC cells by secreted by internalized ExoS-GAP(yellow arrows, insets show enlargement of close association of ExoS-GAP()), also provides an explanation for the more efficient internalization and secretion of ExoS within cells, Pa internalization. The finding that ExoS-WT is secreted by internalized Pa within MTLn3 cells, whereas ExoS-WT is predominately T3S translocated into MTC cells by external Pa, also provides an explanation for the more efficient ADP-ribosylation of RalA in MTC cells, as ExoS would have an opportunity to gain access to membrane associated RalA during the T3S translocation process.

Characterization of the target of ExoS-GAP activity that differentiates Pa infection in MTLn3 and MTC cells, ExoS translocation was monitored following treatment of both cell lines with Y-27632, an inhibitor of p160 Rho associated protein kinase (ROCK), which is a major downstream effector of Rho GTPase activity associated with tumor invasion (de Toledo et al., 2012). In this regard, previous studies in MTLn3 cells found that inhibition of either Rho GTPase or ROCK (Rho/ROCK) activity led to the reciprocal activation and localization of Rac1 to newly formed protrusions in MTLn3 cells (El-Sibai et al., 2008). As a control, both cell lines were treated with NSC23766, a Rac1 inhibitor, which is predicted to have no effect on T3S translocation in MTLn3 cells.

In ROCK inhibition studies, MTC and MTLn3 cells were starved for 3 hr prior to the addition of 25 μM ROCK inhibitor, Y-27632, for 30 min. Phase contrast images show that treatment with ROCK inhibitor for 30 min caused severe contraction of the edge becoming severely contracted. Following treatment with ROCK inhibitor, cells were either uninfected or co-cultured for 3.5 hr with Pa ExoS-WT, Pa ExoS-GAP(−), or Pa ExoS-ADPRT(−) in the presence of inhibitor under steady-state conditions. When ExoS translocation was assayed in MTC cells following treatment with ROCK inhibitor, no significant alteration in the ExoS translocation pattern was detected following co-culture with Pa ExoS strains as compared with non-ROCK inhibitor treated cells (Fig. 5B). In contrast,
treatment of MTLn3 cells with ROCK inhibitor caused a significant decrease in translocation by Pa ExoS-WT (P<0.003) and Pa ExoS-ADPRT(−) (P<0.002), while causing no significant alteration in Pa ExoS-GAP(−) translocation. Myosin II regulatory light chain (RLC) is one of several substrates phosphorylated by ROCK, and when RLC phosphorylation was used to assess inhibition of ROCK activity by Y-27632, a decrease in both mono- (P1) and di- (P2) phosphorylated myosin II regulatory light chain (RLC) was detected in cell lysates following treatment of MTC or MTLn3 cells with ROCK inhibitor and co-culture with Pa strains (Fig. 5B). Alternatively, when both cell lines were starved for three hours, and then treated with 50 μM NSC23766 for 12–16 hr to inhibit Rac1 activity prior to co-culture with Pa strains, no significant alteration in ExoS translocation in either MTC or MTLn3 cells was detected (data not shown). In summary, these experiments found that treatment of MTLn3 cells with ROCK inhibitor altered their ExoS translocation pattern to one similar to that of MTC cells, while treatment of MTC cells with ROCK inhibitor, or treatment of both cell lines with Rac1 inhibitor, caused no significant alterations in ExoS translocation. Collectively our results are consistent with activation of Rho/ROCK, but not Rac1, mediating increased translocation of ExoS-WT in highly metastatic MTLn3 cells, and highlight the ability of Pa ExoS-GAP activity to function as a biological probe to detect alterations in MTLn3 cell properties linked to metastasis.

Discussion

The high susceptibility of cancer patients to P. aeruginosa infections is generally attributed to immnosuppression and systemic compromises associated with cancer treatments. As a result, the possibility that alterations at the tumor cell level might contribute to Pa infection remains relatively unexplored. In focusing on how metastatic properties of tumor cells might influence Pa infection, we found that ExoS translocation was more efficient in highly metastatic MTLn3 cells as compared to treatment of MTLn3 cells with ROCK inhibitor caused a significant decrease in translocation by Pa ExoS-WT (P<0.003) and Pa ExoS-ADPRT(−) (P<0.002), while causing no significant alteration in Pa ExoS-GAP(−) translocation. Myosin II regulatory light chain (RLC) is one of several substrates phosphorylated by ROCK, and when RLC phosphorylation was used to assess inhibition of ROCK activity by Y-27632, a decrease in both mono- (P1) and di- (P2) phosphorylated myosin II regulatory light chain (RLC) was detected in cell lysates following treatment of MTC or MTLn3 cells with ROCK inhibitor and co-culture with Pa strains (Fig. 5B). Alternatively, when both cell lines were starved for three hours, and then treated with 50 μM NSC23766 for 12–16 hr to inhibit Rac1 activity prior to co-culture with Pa strains, no significant alteration in ExoS translocation in either MTC or MTLn3 cells was detected (data not shown). In summary, these experiments found that treatment of MTLn3 cells with ROCK inhibitor altered their ExoS translocation pattern to one similar to that of MTC cells, while treatment of MTC cells with ROCK inhibitor, or treatment of both cell lines with Rac1 inhibitor, caused no significant alterations in ExoS translocation. Collectively our results are consistent with activation of Rho/ROCK, but not Rac1, mediating increased translocation of ExoS-WT in highly metastatic MTLn3 cells, and highlight the ability of Pa ExoS-GAP activity to function as a biological probe to detect alterations in MTLn3 cell properties linked to metastasis.

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The high susceptibility of cancer patients to P. aeruginosa infections is generally attributed to immnosuppression and systemic compromises associated with cancer treatments. As a result, the possibility that alterations at the tumor cell level might contribute to Pa infection remains relatively unexplored. In focusing on how metastatic properties of tumor cells might influence Pa infection, we found that ExoS translocation was more efficient in highly metastatic MTLn3 cells as compared to...
non-metastatic MTC cells. Pa is primarily an extracellular pathogen, but further analysis revealed that increased ExoS translocation into MTLn3 cells directly correlated with Pa internalization and secretion of ExoS within MTLn3 cells, which contrasts with conventional T3S translocation by extracellular Pa through a T3S membrane translocon channel. Differences in MTLn3 and MTC cell responsiveness to Pa ExoS related to reactivity to ExoS-GAP activity. In turn, inactivation of ExoS-GAP by an R146A mutation eliminated differences in the susceptibility of MTC and MTLn3 cell to Pa infection as assessed based on ExoS translocation and Pa internalization. ExoS-GAP activity targets Rho family proteins, and inhibition of ROCK activity, a downstream effector of Rho GTPase activity associated with tumor invasion (de Toledo et al., 2012), significantly decreased ExoS translocation into MTLn3 cells. The finding that Rho/ROCK signaling in MTLn3 cells enhanced Pa internalization, and that this resulted in increased ExoS transfer into MTLn3 cells identifies one property of metastatic tumor cells that can alter sensitivity to Pa infection.

The ability of Pa-ExoS to differentially infect MTC and MTLn3 cells based on their metastatic properties introduces the interesting possibility that reactivity to Pa ExoS might serve as a tool to predict or detect the metastatic potential of neoplastic tissue. Tumor progression to metastasis is a complex process that involves modulations of cell adhesion, migration, and extracellular matrix (Struckhoff et al., 2011). This complexity has complicated detection and delineation of the metastatic processes. The possibility that Pa ExoS can serve as a tool for assessing the metastatic potential of tumors is predicated on the ability of Pa to infect migrating (invasive) cells, and the ability of ExoS to target eukaryotic cell proteins that mediate tumor progression and metastasis, including Rho-GTPases, Ras family proteins, ERM proteins, vimentin and cyclophilin A (Struckhoff et al., 2011; Bos, 1988; Curto and McClatchey, 2004; Lee and Kim, 2010; Satelli and Li, 2011). Interestingly, the focus of this study became ExoS-GAP activity, which served as a functional probe to differentiate Rho GTPase activity in MTC and MTLn3 cells. Previous studies comparing Rac and Rho activity in MTC and MTLn3 cells found MTC cells to have decreased RhoA activity, increased Rac activity and to utilize Rac to produce membrane protrusions that mediate cell migration (El-Sibai et al., 2008). MTLn3 cells in comparison were characterized as having increased RhoA activity, decreased Rac activity, and to project Cdc42 mediated membranes protrusions during cell migration (El-Sibai et al., 2007; Yip et al., 2007). Notably, the phenotype of Rho/ROCK activation at the leading edge of MTLn3 cells could be switched to Rac1 driving cell protrusion by treatment with a ROCK inhibitor (El-Sibai et al., 2008), just as the phenotype of enhanced ExoS translocation in MTLn3 cells could be switched to low ExoS translocation by treatment with a ROCK inhibitor. The finding that Pa infection and ExoS translocation can differentiate Rac1 (non-metastatic) or RhoA (metastatic) properties of MTC or MTLn3 cells, and detect the reversal of these properties following treatment with ROCK inhibitor, draws attention parallels between Pa infection and tumor metastasis. Evidence that Pa ExoS-GAP activity can discriminate differences in Rho GTPases in tumor cells, beyond Rho or Rac activation, was provided by IF studies, which found MTC cells to contract but retain stably adhered branched actin filaments in response to Pa ExoS-GAP, which contrasted with the response of MTLn3 cells, where leading edge architecture was replaced with actin microspikes. The precise mechanisms underlying morphological differences in MTC and MTLn3 cell responsiveness to ExoS-GAP activity remain unknown, but they identify previously unrecognized differences in adhesion properties of MTC and MTLn3 cells, which might prove applicable to diagnosis of metastatic tumors.

The possibility that Pa-ExoS might also serve as a biological probe to dissect cellular mechanisms that underlie tumor metastasis is founded on interesting similarities between Pa infection and tumor development. For example, the finding that increased levels of ExoS transfer into metastatic MTLn3 cells related to Pa internalization draws attention to relationships between membrane properties that facilitate Pa internalization and those associated with tumor metastasis. Pa is predominately an extracellular pathogen, and susceptibility to infection and Pa internalization is influenced by epithelium integrity and polarity (Fleiszig et al., 1997; Plotkowski et al., 1999). In studies of MDCK epithelial cells, Pa internalization was enhanced in incompletely polarized monolayers in association with Rho activation and decreased in highly polarized monolayers in conjunction with Cdc42 activation (Kazmierczak et al., 2004). In our studies, inhibition of ROCK activity significantly decreased ExoS translocation into MTLn3 cells, consistent with Rho/ROCK activation mediating enhanced Pa internalization in MTLn3 cells. Rho/ROCK signaling also mediates amoeboid migration and membrane blebbing that enhance tumor cell invasiveness (Struckhoff et al., 2011). The possibility that membrane blebbing might be a common basis for Pa internalization and tumor metastasis is supported by a recent study that identified the ability of Pa to enter, survive and replicate within membrane blebs of corneal epithelial cells, in an ExoS-ADPRT dependent manner (Angus et al., 2010). Membrane blebbing is a rapid, dynamic process, and a core element in bleb formation is retraction of the plasma membrane, which is mediated by signaling through Rho/ROCK and actinomycin contractility (Charras and Paluch, 2008). Thus, comparisons of tumor metastasis with Pa internalization find that both processes are facilitated by Rho/ROCK activation and by membrane bleb formation. The possibility that Rho/ROCK mediated membrane blebs might contribute to Pa internalization in MTLn3 cells is supported by the detection of blebbing in MTLn3 cells, but not MTC cells, following infection of with Pa ExoS-GAP(−) that maintains ExoS-ADPRT activity (supplementary material Fig. S1). Functional similarities between membrane blebs that mediate bacterial internalization and tumor metastasis have not previously been realized, and awareness of these similarities provides a new perspective on alterations in membrane properties that occur in association with tumor metastasis.

To summarize, in using metastatic MTLn3 cells and non-metastatic MTC cells as cell culture models to study Pa infection we were able to confirm that alterations at the tumor cell level can contribute to the establishment of Pa infection. Mechanically enhanced Pa infection in MTLn3 cells related to Rho/ROCK activation, which drives cell migration and membrane plasticity during tumor cell invasion, and also facilitates Pa internalization. This is the first study to characterize a mechanism underlying the increased susceptibility of cancer patients to Pa infection at the cellular level. Reactivity to T3S translocated ExoS also allowed recognition of functional differences in Rho GTPase activity between MTC and MTLn3 cells that extend beyond Rac1 and...
Rho activation. Notably, commonalities observed between tumor development and Pa infection, along with the finding that reactivity to Pa ExoS can differentiate non-metastatic and metastatic properties of MTC and MTLn3 cells, introduces the notion that Pa ExoS might serve as a biological tool to assess the metastatic properties of neoplastic tissue. While further studies are required to determine how Pa ExoS will respond to different tumorigenic states, the ability of ExoS to target and alter the function of multiple tumor-associated proteins provides the diversity needed to accommodate tumor heterogeneity.

Materials and Methods

Bacterial strains

_P. aeruginosa_ strain PA103AUT is T3S effector-less derivative of strain PA103 that maintains an intact T3S system (Vallis et al., 1999). This strain was used to express: 1) plasmid encoded HA-tagged wild type ExoS, 2) ExoS with mutations that detect HA-tagged ExoS effector, anti-PopB (provided by John Condeelis (Albert Einstein College of Medicine, Bronx NY) and Jonathan Backer (Albert Einstein College of Medicine), respectively. Both cell lines were cultured in Minimal Essential Medium. Alpha (MEM; Cellgro, Manassas VA), containing nonessential amino acids (Cellgro), 10% fetal bovine serum (FBS; Hyclone, Logan UT), 100 U/ml penicillin, and 100 μg/ml streptomycin (Hyclone).

Analysis of Pa-T3S translocation

Pa-T3S translocation was assayed by monitoring transfer of the T3S effector, ExoS, and T3S toxin protein, PopB, into membrane fractions following coculture with Pa strains. For these analyses, MTC and MTLn3 cells were seeded at 2×10⁶ and 2.5×10⁶ cells/ml, respectively, in 60 mm dishes (Corning Inc., Corning, NY) and grown for 48 hr. Prior to addition of bacteria, cells were washed with Dulbecco's phosphate buffered saline (DPBS; Hyclone) and starved for 3–12 hr in MEM containing 0.6% BSA. Following co-culture, bacteria were removed, cells were washed twice with DPBS containing 200 μg/ml ciprofloxacin and detached with trypsin. An aliquot of cells was lysed and analyzed for total protein (BCA Protein Assay, Pierce). Remaining cells were resuspended in DPBS containing ciprofloxacin and lysed in Laemmli sample buffer. Whole cell lysates were analyzed by SDS-11% PAGE and immunoblot analysis as above, using anti-HA to detect T3S translocated ExoS effectors, anti-RalA to assess T3S translocated ExoS-ADPRT activity, and anti-glyceroldehyde 3-phosphate dehydrogenase (GAPDH) (Millipore, Temecula CA) to monitor protein loading of whole cell lysates. To detect inhibition of ROCK activity by Y-27632 in conjunction with analysis of ExoS translocation, whole cell lysates were re-analyzed by SDS-14% PAGE, and myosin II light chain phosphorylation was detected using an affinity purified rabbit anti-phospho Thr18/Ser19 RLC antibody (Chew et al., 1998). ExoS effector translocation was quantified by densitometry analysis using ImageJ 1.40 g software.

Statistical analysis

JMP Version 9 Software (SAS Institute, Cary, NC) was used for statistical analysis, and significance was determined by a two-sided alpha level set at P<0.05. One-way ANOVAs were used to evaluate differences among Pa strains between cell lines. Multiple comparisons were analyzed with a Tukey’s HSD test for ExoS translocation and Pa internalization. A T-test was used to evaluate differences in ROCK and Rac1 inhibitor studies.

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Competing Interests

The authors have no competing interests to declare.

References


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microscope (Jena, Germany) and exported to Adobe Photoshop CS4 Extended (Adobe Systems Inc., San Jose, CA) as 8 bit TIFF files. Channels in IF images were pseudocolored as indicated to improve visibility.

Inhibition Rho and Rac activity

To assess the role of Rho and Rac in Pa-T3S translocation, MTC and MTLn3 cells were seeded in 60 mm dishes, as described above, and starved for 3 hr prior to addition of inhibitors. Rho activity was inhibited by treating cells for 30 min in starvation medium with 25 μM Y-27632 (Cayman Chemical Company, Ann Arbor, MI), an inhibitor of p160 Rho associated protein kinase (ROCK), which is a downstream effector of Rho GTPase activity known to influence cell invasion (de Toledo et al., 2012). Rac1 activity was inhibited by treating cells for 12–16 hr with 50 μM NSC27676 (EMD Chemicals, Gibbstown, NJ) in starvation medium. Effects of the drugs on cell morphology were visualized with a LD A-Plan20/0.3 Ph1 objective on a Zeiss Axiovert 200 microscope (Jena, Germany). Images were exported to Adobe Photoshop CS4 Extended (Adobe Systems Inc.) as TIFF files and cropped.

Following treatment with inhibitor, cells were co-cultured with Pa strains for 3.5 hr in the presence of inhibitor in MEM containing 5% FBS. Cells were then washed twice with DPBS containing 200 μg/ml ciprofloxacin and detached with trypsin. An aliquot of cells was lysed and analyzed for total protein (BCA Protein Assay, Pierce). Remaining cells were resuspended in DPBS containing ciprofloxacin and lysed in Laemmli sample buffer. Whole cell lysates were analyzed by SDS-11% PAGE and immunoblot analysis as described above, using anti-HA to detect T3S translocated ExoS effectors, anti-RalA to assess T3S translocated ExoS-ADPRT activity, and anti-glyceroldehyde 3-phosphate dehydrogenase (GAPDH) (Millipore, Temecula CA) to monitor protein loading of whole cell lysates. To detect inhibition of ROCK activity by Y-27632 in conjunction with analysis of ExoS translocation, whole cell lysates were re-analyzed by SDS-14% PAGE, and myosin II light chain phosphorylation was detected using an affinity purified rabbit anti-phospho Thr18/Ser19 RLC antibody (Chew et al., 1998). ExoS effector translocation was quantified by densitometry analysis using ImageJ 1.40 g software.


