



HAL
open science

The Phosphatase PRL-3 Is Involved in Key Steps of Cancer Metastasis

Laura Duciél, Luis Cristobal Monraz Gomez, Maria Kondratova, Inna Kuperstein, Simon Saule

► **To cite this version:**

Laura Duciél, Luis Cristobal Monraz Gomez, Maria Kondratova, Inna Kuperstein, Simon Saule. The Phosphatase PRL-3 Is Involved in Key Steps of Cancer Metastasis. *Journal of Molecular Biology*, 2019, 431, pp.3056 - 3067. 10.1016/j.jmb.2019.06.008 . hal-03487705

HAL Id: hal-03487705

<https://hal.science/hal-03487705>

Submitted on 20 Dec 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Changes are shown in red

The phosphatase PRL-3 is involved in key steps of **cancer metastasis**

Laura DUCIEL^{1,2*}, Luis Cristobal MONRAZ GOMEZ^{3,4,5*}, Maria KONDRATOVA^{3,4,5}, Inna KUPERSTEIN^{3,4,5}
and Simon SAULE^{1,2}

1. Institut Curie, PSL Research University, Centre National de La Recherche Scientifique (CNRS), Institut National de la Santé Et de la Recherche Médicale (INSERM), Unité Mixte de Recherche 3347 (UMR), Unité 1021 Orsay, France. 2. Université Paris Sud, Université Paris-Saclay, Centre National de La Recherche Scientifique, Unité Mixte de Recherche 3347, Unité 1021, Orsay, France. 3. Institut Curie, PSL Research University, F-75005 @Paris, France. 4. INSERM, U900, F-75005 Paris, France. 5. MINES ParisTech, PSL Research University, CBIO-Centre for Computational Biology, F-75006 Paris, France.

*These authors contributed equally

Joint corresponding authors:

Simon SAULE

Institut Curie, Section Recherche

UMR3347/U1021

Campus Universitaire d'Orsay Bâtiment 110

91405 Orsay Cedex

Tel: 00 33 (1) 69 86 71 53

Fax: 00 33 (1) 69 86 30 51

Inna Kuperstein

U900 Institut Curie – INSERM - Mines ParisTech

Department of Bioinformatics and Computational Systems Biology of Cancer

Institut Curie - 26 rue d'Ulm - 75248 PARIS cedex 05 - France

Inna.kuperstein@curie.fr

Tel: +33 (0) 1 56 24 69 87

<http://www.curie.fr> <http://u900.curie.fr> <http://sysbio.curie.fr>

Highlights: The phosphatase PRL-3 regulates numerous pathways driving tumorigenesis and metastasis

Abbreviations: PTP4A3, protein tyrosine phosphatase 4A3; PRL, phosphatase of regenerating liver; EMT, epithelial-to-mesenchymal transition; PTP, protein tyrosine phosphatase; MMPs, metalloproteases.

Abstract

PRL-3 belongs to the PRL phosphatase family. Its physiological role remains unclear, but many studies have identified PRL-3 is a marker of cancer progression and shown it to be associated with metastasis. Evidence implicating PRL-3 in various elements of the metastatic process, such as the cell cycle, survival, angiogenesis, adhesion, cytoskeleton remodelling, EMT, motility and invasion has been reported. Furthermore, several molecules acting as direct or indirect substrates have been identified. However, this information was obtained in many different studies and it remains difficult to see the larger picture. We therefore systematically collected the published information together and used it to develop a comprehensive signalling network map. By analysing this network map, we were able to retrieve the signalling pathways via which PRL-3 governs the key steps of the metastatic process in cancer. In this review, we summarise current knowledge of the role of PRL-3 in cancer and the molecular mechanisms involved. We also provide the web-based open-source PRL-3 signalling network map, for use in further studies.

Keywords: phosphatase, signalling pathways, tumorigenesis, metastasis, systems biology, web-based resource, comprehensive signalling network map, reduced models

Introduction

Tumorigenesis is a gradual multi-step process, **by which** cells acquire new biological capacities that **facilitate** tumor formation and **dissemination, eventually resulting in metastasis**^{1,2}. The first step **in this process is cell** transformation and tumor growth due to uncontrolled proliferation. This proliferative capacity **results from the acquisition of resistance to** apoptosis, cell cycle deregulation and **cell survival** pathways. **The deregulation of** angiogenic pathways **leads to** neovascularisation of the tumor, which is important for tumor growth, but also for metastatic colonisation. Finally, **tumor cells must acquire the capacity to migrate, through the epithelial-to-mesenchymal transition (EMT), supported by cytoskeleton reorganisation and changes to cell adhesion, if they are to invade distant organs**³.

Multiple signalling pathways are **involved** in this sequence of events, promoting **the transition from a normal cell to an invasive** cancer cell. PTPs (protein tyrosine phosphatases) constitute a large family of enzymes **playing crucial roles** in the regulation of many key signalling pathways involved in the control of cell proliferation, adhesion, migration, differentiation, survival and apoptosis, **for example**⁴. The deregulation of PTP **activity, resulting in** aberrant tyrosine phosphorylation, has been implicated in the progression of various diseases, including cancer⁵.

PRLs (phosphatases of regenerating liver) **belong to the** dual-specificity phosphatase (DSP) subgroup of PTPs. PRLs are small (22 kDa), **closely related** proteins, with amino-acid sequences displaying **at least** 75% identity⁶. PRLs **have been** conserved during evolution and are expressed during embryonic development⁷, **particularly in the** skeletal muscle of vertebrates⁸. PRLs have an N-terminal catalytic domain containing the PTP active-site sequence CX5R, in which cysteine is the catalytic residue⁹, and a C-terminal CAAX prenylation sequence important for membrane association and intracellular localization⁹. Prenylated PRLs are associated with plasma membrane

localization in early endosomes and autophagosomes, **whereas** non-prenylated PRLs are **redistributed** to the nucleus^{10–13}.

The phosphatase of regenerating liver-3 (**encoded by PRL-3, and also known as** tyrosine phosphatase 4A3 (PTP4A3)) , belongs to the PRL phosphatase family, **which has** three members: PRL-1, PRL-2 and PRL-3. The gene encoding PRL-3 is located **on chromosome** 8q24.3. In human adult tissues, PRL-3 is **present principally in the** skeletal muscle and heart, with lower levels in other tissues, such as the retina, liver and pancreas¹⁴.

Little is known about the physiological roles of PRLs, but they have been implicated in cell proliferation, migration, invasion, tumor growth and metastasis⁶. Interestingly, the inhibition of prenylation, **leading to the translocation of PRLs to the nucleus, abolishes the** pro-migratory and pro-metastatic effects of these enzymes in cancer^{15–18}. PRL-3 was the first member of the PRLs found **to be more strongly expressed** in liver metastases of colon cancers **than in healthy** colon tissue or primary tumors¹⁹. PRL-3 **is also the most widely studied PRL , due to its involvement in various types of cancer. PRL-3 is known to be involved in the metastatic processes of many different human cancers, including** gastric cancers²⁰, ovarian cancers^{21,22}, cervical cancer²³, non-small cell lung cancer²⁴, liver cancer^{25,26}, human gliomas²⁷, nasopharyngeal carcinoma²⁸, **oesophageal** cancer²⁹, metastatic colorectal carcinomas (CRCs)^{30,31}, breast cancer³², uveal melanoma³³, cervical cancer³⁴, salivary adenoid cystic carcinoma³⁵ myeloid leukemia³⁶ and multiple myeloma³⁷.

The mechanism of action and intracellular substrates of PRL-3 remain largely unknown, **which has led to many studies of the substrates of** PRL-3 substrates, and the pathways and mechanisms in which this phosphatase is involved. We used a systems biology approach **to** integrate published **evidence about the molecular mechanisms of action of PRL-3** into a comprehensive map of

molecular interactions. The resulting comprehensive PRL-3 signalling map summarizes current knowledge on this topic. We also performed a structural network analysis to identify the main players in various key steps in the metastatic transformation of cancer cells governed by PRL3. We extracted minimal reduces models for the key pathways to major phenotypes during invasion. These diagrams can be used for the modelling of cell metastasis in cancer. This work makes it possible summarise, systematically and visually, what is known about PRL_3 in tumorigenesis and the multifaceted process of metastasis, as discussed in this review. We describe the action of PRL-3 in enabling cells to acquire the biological capabilities required for tumor development and invasion.

Construction and annotation of the signalling network map

We manually retrieved scientific discoveries concerning the molecular mechanisms of action of PRL-3 from previous publications and systematically gathered them together into a comprehensive signalling map, according to a well-established procedure³⁸ (Supplementary Figure 1). We performed a literature search to identify studies of PRL-3, using the keywords “PRL-3” and “PTP4A3”, and we selected the references linking this phosphatase to cancer and invasion. We then depicted the molecular mechanisms described in these references graphically, in the form of a biochemical reaction network, with the Cell Designer tool³⁹ and Systems Biology Graphical Notation⁴⁰ syntax. The software creates a structured network representation in Systems Biology Markup Language⁴¹, which can then be used for further computational analyses.

All entities depicted in the map are assigned common identifiers converted into links to the corresponding entity descriptions in the HGNC, UniProt, Entrez, GeneCards, Reactome, and Kegg databases, and the corresponding literature references are provided (Supplementary figure 2). The entities on the map are annotated in NaviCell format (<https://navicell.curie.fr/doc/NaviCellMapperAdminGuide.pdf>).

Structural analysis of the network and model reduction

For identification of the mechanisms by which PRL-3 regulates various phenotypes during invasion, we reduced the complexity of the map through a path analysis of the map with the OCSANA algorithm⁴² in the BiNoM⁴³ plugin of Cytoscape⁴⁴. Subnetworks containing major paths and players connecting PRL-3 and the six major phenotypes of interest (cell cycle; survival; angiogenesis; adhesion; cytoskeleton remodelling; and EMT, motility and invasion), were retrieved. These phenotype-specific subnetworks of the PRL-3 map were annotated with module tags (as further explained) and used to create functional module maps accessible from the NaviCell page. The RPL-3 map thus has a hierarchical structure, and each module can be visualised in the context of the global map or individually (Supplementary Figure 3).

We used the paths identified on the map to guide the further reduction of complexity of the subnetworks, by maintaining first-order connections, but removing unrelated processes from the subnetwork. This reduction made it easier to understand the principles underlying the organisation of the map and to identify the key paths. Diagrams of the reduced models relating to the regulation of the six aforementioned phenotypes were generated and are represented in Figures 1-3.

Module tagging

Each entity in the map can participate in one or several functional modules. The corresponding module tags are systematically assigned in the annotation of the map entities and converted into links by the NaviCell factory during the process of online map generation (Supplementary figure 2). The links can be used to trace the participation of entities in the different modules of the map and to facilitate shuttling between the module maps and the general map. The list of module tags corresponds to the list of functional modules and to the model diagrams in Figures 1-3.

Map availability and navigation

The comprehensive modular map is an open-source map accessible via several web-based platforms, such as NaviCell⁴⁵, MINERVA⁴⁶ and NDeX⁴⁷, facilitating map navigation and curation by the community. The resource is accessible via https://navicell.curie.fr/pages/maps_PRL3.html. Each module map can be accessed separately, to facilitate use of the map. We also provide downloadable materials, such as PPI networks extracted from the map, lists of references annotating the map and module content lists in a format suitable for enrichment analysis studies.

PRL-3 signalling in cell cycle, survival and apoptosis

PRL-3 is involved in tumor development, through control of cell cycle, apoptosis and survival processes. p53 is known to affect the transcription of the PRL-3 gene⁴⁸, but PRL-3 can also downregulate p53 expression in cancer cells by inducing the transcription of gene encoding PIRH2 and increasing the phosphorylation of MDM2, both of which downregulate p53⁴⁹, or by downregulating expression of the alternative reading frame of p14 (p14^{ARF})⁵⁰.

PRL-3 interacts with the telomere-related protein RAP1, which is responsible for telomere lengthening, thereby regulating the NF-κB signalling pathway, by upregulating the expression and phosphorylation of p65⁵¹. PRL-3 also promotes cell proliferation by upregulating KCNN4 channels, in an NF-κB dependent manner, hence facilitating G2/M transition⁵². A study on triple-negative breast cancer (TNBC) demonstrated that PRL-3 knockdown results in G1 cell arrest, inducing a TNFα response, which leads to cell senescence through the TNF-R1-mediated activation of NF-κB, followed by apoptosis, due to an increase in TNF-R1 signalling through the TNFα-associated extrinsic death pathway, shunting signalling away from the NF-κB cascade⁵³.

In mouse embryonic fibroblasts (MEFs), PRL-3 overexpression induces G1 arrest downstream p53, by triggering a PI3K-Akt-activated negative feedback loop⁴⁸. PRL-3 has also been shown to promote proliferation by activating the Akt/mTOR pathway⁵⁴. Akt/mTOR signalling regulates apoptosis, cell growth, cell cycle and angiogenesis. PRL-3 can induce mTOR phosphorylation, leading to downstream signalling activation via mTOR substrates, such as p70S6K and 4E-BP1⁵⁵. A recent study also highlighted cooperation between the AKT/mTOR and WNT/ β -catenin signalling cascades in PRL-3-high acute myeloid leukemia (AML)⁵⁶.

The downregulation of PRL-3 also inhibits proliferation and apoptosis induced by emodin in the SGC-7901 human gastric carcinoma cell line⁵⁷. PRL-3 has been shown to induce hyperactivation of EGFR and its downstream signalling cascades in multiple human cancer cell lines⁵⁸. Finally, PRL-3 overexpression in multiple myeloma (MM) increases survival, STAT3 phosphorylation and the number of cells in G2/M and decreases the number of cells in the S and G1 phases⁵⁹. Remarkably, in colon cancer, the increase in STAT3 phosphorylation induced by PRL-3 triggers the expression of miR-21, miR-17 and miR-19a, which directly target PTEN⁶⁰.

All of these results indicate that PRL-3 is involved in control of cell cycle phases transition via the regulation of the major player p53, thus promoting proliferation and inhibiting apoptosis (Figure 1A).

PRL-3 signalling in angiogenesis

Guo *et al.* provided the first evidence for the role of PRL-3 in tumor angiogenesis in 2006. They reported that the expression of PRL-3 in foetal heart, developing blood vessels and immature erythrocytes, but not in their mature counterparts, suggesting an essential role for PRL-3 in early angiogenic events. They then investigated the functions of PRL-3 in tumor angiogenesis, demonstrating that Chinese hamster ovary (CHO) cells and DLD-1 human colon cancer cells

expressing PRL-3 could **attract migrating** human umbilical vascular endothelial cells (HUVEC), **and** that DLD-1 cells could enhance **vessel formation by** HUVEC⁶¹. Furthermore, after injecting CHO cells expressing PRL-3 into nude mice, **the authors** observed the recruitment of host endothelial **cells to the tumors and the** initiation of angiogenesis. Interestingly, PRL-3-expressing cells decreased interleukin-4 (IL-4) levels, thus **attenuating the inhibitory effects of** IL-4 on the HUVEC vasculature⁶¹. VEGF can also promote PRL-3 gene transcription, by inducing expression of the transcription factor MEF2C⁶².

Another study showed that PRL-3 participates in VEGF signalling, potentially via Src activation, **promoting** angiogenesis in primary cultures of murine and human endothelium⁶³. Finally, in endometrial adenocarcinoma, PRL-3 induces microvascular vessel formation by promoting VEGF expression via the upregulation of phosphorylated extracellular signal-regulated kinase (pERK)⁶⁴. **Similar findings have also been reported for** lung cancer cells²⁴ (Figure 1B).

PRL-3 signalling in adhesion

Several studies **have shown** that PRL-3 promotes cancer invasion and metastasis by regulating cell adhesion. Peng *et al.* were the first to identify integrin $\alpha 1$ as **a protein interacting with** PRL-3⁶⁵ by co-immunoprecipitation assays. PRL-3 **was subsequently shown to interact with and downregulate** the tyrosine phosphorylation of integrin $\beta 1$ ^{18,66}, particularly for Y783, a key residue for integrin $\beta 1$ function⁶⁷. PRL-3 also regulates integrin $\alpha 2$ by suppressing c-fos expression, and decreases production and phosphorylation of paxillin in ovarian cancer cells⁶⁸. The downregulation of paxillin by PRL-3 **has also been** reported in HeLa cells⁶⁹. In addition, PRL-3 regulates integrin $\alpha 5$ recycling through Arf1 activity⁷⁰. JAM2, a junctional adhesion molecule, was recently **shown to interact with** PRL-3 in colon cancer⁷¹. **Consistent with these** observations, PRL-3 **has been shown to mediate** SDF-1 α -stimulated calcium release **in acute lymphoblastic leukaemia, leading to the activation of** focal

adhesion kinase (FAK) and Src, important effectors for migration and adhesion⁷². Finally, PRL-3 can also dephosphorylate phosphatidylinositol⁷³ and increase the phosphorylation of Erk1/2⁷⁴ (Figure 2A).

PRL-3 signalling in cytoskeleton remodelling

PRL-3 substrates remain incompletely characterised, but three cytoskeletal proteins have been identified as PRL-3 targets, providing strong evidence of a role for PRL-3 in promoting migration and invasion by cytoskeleton remodelling.

The first substrate of PRL-3 to be identified was Ezrin. Ezrin belongs to the ERM protein family, which links cell surface receptors and the actin cytoskeleton. PRL-3 decreases Ezrin phosphorylation, and *in vitro* phosphatase assays suggested that PRL-3 affected Ezrin-pThr567 in endothelial cells, thereby promoting tumor progression⁷⁵.

The cytoskeletal intermediate filament keratin 8 (KRT8) was also identified as a PRL-3 substrate. PRL-3 and KRT8 interact physically and are colocalised at cellular lamellipodia and ruffles *in vivo*. PRL-3 expression decreases or abolishes KRT8 phosphorylation, particularly at the invasive front and in liver metastases, suggesting a possible role for PRL-3 in cell migration and metastasis in colon carcinoma via KRT8 dephosphorylation⁷⁶.

Finally, Stathmin, a key oncoprotein, is also a cytoskeletal PRL-3-associated protein. Stathmin is involved in controlling microtubule dynamics. It interacts with PRL-3 in colon cancer cells, leading to microtubule destabilisation, thereby contributing to the progression and metastasis of CRC⁷⁷.

Other studies have shown that PRL-3 can modulate the cytoskeleton by regulating Rho family GTPases. In SW480 colorectal carcinoma cells expressing exogenous PRL-1 and PRL-3, the activation of Rho and, RhoC, and the and consequent PRL-mediated motility and invasion were blocked by inhibition of Rho kinase (ROCK), a key Rho effector. Furthermore, PRL PTPs decreased Rac activity without affecting Cdc42 activity¹⁶. PRL-3 also increases the activity of RhoA and mDia1 in lung cancer, promoting actin polymerisation and increases in migration and invasion⁶⁵. The activation of RhoC by PRL-3 was confirmed by additional studies^{78,79}, showing that in CHO cells expressing PRL-3, the levels of active RhoA and Rac1 were reduced, that coincided with a reduction of actin filaments⁶⁹. The effects of PRL-3 on RhoA and probably on the other Rho GTPases, might be cell type dependent or fluctuate according to the biological context (Figure 2B).

PRL-3 signalling in EMT and motility

PRL-3 also plays a crucial role in epithelial-to-mesenchymal transition (EMT). EMT is an physiological process that occurs during embryonic development. In *Xenopus laevis*, PRL-3 is required for cephalic neural crest migration *in vivo*, which is essential for embryonic development⁸⁰. The same EMT mechanism guides the transformation of epithelial cells into cells with a mesenchymal phenotype in cancer, facilitating their migration and the formation of metastases. PRL-3 is known to initiate EMT in cancer cells by activating the Akt pathway. Wang *et al.* were the first to report, in 2007, that PRL-3 activates Akt by downregulating PTEN expression, inhibiting GSK-3 β , and thereby causing an increase in mesenchymal markers, such as fibronectin and Snail, and a decrease in epithelial markers, as E-cadherin, γ -catenin and integrin β 3⁶⁹. The activation of the Akt pathway by PRL-3 was subsequently confirmed in other studies^{54,81-84}. PRL-3 has also been shown to promote EMT by directly downregulating E-cadherin and CDH22 expression^{85,86}. Another study showed that PRL-3 downregulated PTEN by dephosphorylating NHERF1 in the nucleus, leading to the translocation of both PTEN and NHERF1 from the nucleus to the cytoplasm⁸⁷. Moreover, in colon cancer cells, PRL-3

induces KCNN4 expression, resulting in Snail expression and a parallel decrease in E-cadherin levels⁸⁸.

Finally, a study on acute myelogenous leukaemia showed that LEO1, a component of RNA polymerase II-associated factor (PAF), activates the expression of SOX2 and SOX4 genes, two potent oncogenes in myeloid transformation. This molecular regulation is positively correlated with PRL-3 levels⁸⁹, again confirming the role of PRL-3 in EMT and motility in cancer (Figure 3A).

PRL-3 signalling in invasion

The link between PRL-3 and the tyrosine kinase Src, a well-known proto-oncogene, seems to be fundamental in the promotion of invasion and metastasis. PRL-3 can promote cell invasion by activating Src⁹⁰, and Src can promote invasion and motility by mediating PRL-3 phosphorylation⁷⁸, highlighting the mutual dependence of these two proteins. PRL-3 induces Src activation by increasing eIF2 phosphorylation, downregulating Csk, a negative Src regulator⁹¹. Furthermore, to clarify the PRL3-mediated signalling network, Walls *et al.* showed that PRL-3 expressing cells display a general increase in protein tyrosine phosphorylation, but that this increase is particularly strong for multiple signalling effectors responsible for Rho-family GTPase, PI3K-Akt, STAT, and ERK activation, suggesting that Src is the primary signal transducer for PRL-3 effects⁹².

Several studies have also highlighted that PRL-3 facilitates tumor cells invasiveness by regulating the extracellular matrix degradation, mediated by matrix metalloproteinases (MMPs). In particular, PRL-3 has been shown to promote invasion by upregulating MMP-10⁹³ in TNBC cells, MMP-7 in human colorectal cancer⁹⁴ and in glioblastoma⁹⁵. Likewise, PRL-3 upregulates MMP-7⁷⁴ and MMP-2/MMP-9 in gastric carcinoma⁸¹. In colon cancer cells, PRL-3 promotes MMP-2 activity by regulating the balance between MMP-2 and TIMP2 (an endogenous inhibitor of MMP-2)⁶⁶. PRL-3 also increases cell membrane accumulation and activity of MMP-14 in uveal melanoma⁹⁶.

Finally, a recent study reported another mechanism by which PRL-3 can promote invasion in colorectal cancer. According to this study, PRL-3 upregulates CCL26, which binds to the CCR3 receptor and induces the mobilization of intracellular Ca^{2+} in TAMs, resulting in an increase in the expression of IL-6 and IL-8 and, thus, an increase in tumor-associated macrophage (TAM) infiltration (see figure 3B)⁹⁷. TAMs play a role in invasion, as they are present in inflammatory infiltrates in tumor tissues and can produce numerous lymphangiogenic growth factors, cytokines, and proteases that promote tumor cell proliferation and metastasis⁹⁸.

Discussion

As described above, PRL-3 modulates the key processes implicated in metastasis, mostly by targeting major signalling pathways, such as the p53, MAPK, mTOR and STAT3 pathways, thereby promoting proliferation and survival. PRL-3 induces angiogenesis via VEGF activation (Figure 4). A strong correlation was found between PRL-3 and Erk levels; Erk is well known to facilitate extracellular matrix adhesion. The effects of PRL-3 on RhoGTPase remain unclear, with some studies reporting that PRL-3 activates RhoA and others reporting that the phosphatase downregulates RhoA expression, and that PRL-3 modulates RhoGTPase to promote cytoskeleton remodelling, EMT and motility, invasion and angiogenesis. The activation of AKT by PRL-3 is also well established and promotes survival, EMT, motility, and invasion. Finally, one of the most important players activated by PRL-3 is the Src kinase, which promotes invasion and metastasis. PRL-3 also acts by regulating some effectors directly. Indeed, this phosphatase directly regulates integrins, FAK and paxillin in focal adhesions and MMPs involved in the degradation of extracellular matrix (Figure 4). PRL-3 also modulates cytoskeleton proteins, such as Ezrin, stathmin and keratin 8, which regulate actin, microtubules and intermediate filaments, respectively.

The involvement of PRL-3 in many cancers suggests that this phosphatase may be a viable therapeutic target. Some PTP inhibitors are already the focus of research studies, but further efforts are required to achieve sufficient selectivity for use in treatment. Numerous molecules have been shown to inhibit PRL-3 via different mechanisms. Some inhibit the phosphatase activity of PRL-3. However, it is also possible to inhibit the anchoring of this molecule to the plasma membrane by inhibiting farnesylation, and the localisation of PRL-3 may regulate its function. For example, it has been shown that preventing PRL-3 anchorage to the plasma membrane with farnesyl transferase inhibitors (FTI) abolishes PRL-3-induced cell migration¹². Unfortunately, most of these studies did not mention the localisation or post translational modification state (phosphorylation, prenylation) of PRL-3, so it remains unclear whether these parameters are crucial for all of its functions.

Details of the signalling of PRL-3 in cancer invasion are now presented in the form of a comprehensive modular signalling map available online. The global map represents the state-of-the-art for knowledge concerning the regulation of metastasis by PRL-3. The modular maps show how each subpart of the multifaceted invasion process is executed. Finally, the simplified diagrams represent executable minimal models, with the main players governing each phenotype during the process.

The PRL-3 map is part of the Atlas of Cancer Signalling Network (ACSN, <https://acs.n.curie.fr>)⁹⁹, and is entitled 'The invasion and motility map'. ACSN is a web-based resource that contains a collection of maps depicting molecular processes in cancer cells and the tumor microenvironment. This tool has many applications that have been reviewed elsewhere¹⁰⁰. This systems biology approach to knowledge representation makes it possible to analyse -omics data in the context of the map, to understand the role of PRL-3-regulated processes in different cancer types. ACSN also forms part of the disease maps community (<http://disease-maps.org>), which aims to apply similar approaches to

the study of different diseases. This partnership facilitates studies of disease comorbidities, and treatment response prediction, for example^{101,102}. This integration with other resources opens up additional opportunities for deciphering the role of PRL-3-related signalling in human diseases other than cancer.

References

1. Hanahan, D., Weinberg, R. a & Francisco, S. The Hallmarks of Cancer Review University of California at San Francisco. **100**, 57–70 (2000).
2. Hanahan, D. & Weinberg, R. A. Hallmarks of cancer: The next generation. *Cell* **144**, 646–674 (2011).
3. Friedl, P. & Wolf, K. Tumor-cell invasion and migration: diversity and escape mechanisms. *Nat. Rev. Cancer* **3**, 362–74 (2003).
4. Alonso, A. *et al.* Protein tyrosine phosphatases in the human genome. *Cell* **117**, 699–711 (2004).
5. Östman, A., Hellberg, C. & Böhmer, F. D. Protein-tyrosine phosphatases and cancer. *Nat. Rev. Cancer* **6**, 307–320 (2006).
6. Rios, P., Li, X. & Köhn, M. Molecular mechanisms of the PRL phosphatases. *FEBS J.* **280**, 505–24 (2013).
7. Lin, M.-D. *et al.* Expression of phosphatase of regenerating liver family genes during embryogenesis: an evolutionary developmental analysis among *Drosophila*, amphioxus, and zebrafish. *BMC Dev. Biol.* **13**, 18 (2013).
8. Zeng, Q., Hong, W. & Tan, Y. H. Mouse PRL-2 and PRL-3, Two potentially prenylated protein tyrosine phosphatases homologous to PRL-1. *Biochem. Biophys. Res. Commun.* **244**, 421–427 (1998).

9. Bessette, D. C., Qiu, D. & Pallen, C. J. PRL PTPs: mediators and markers of cancer progression. *Cancer Metastasis Rev.* **27**, 231–52 (2008).
10. Cates, C. A. *et al.* Prenylation of oncogenic human PTPcaax protein tyrosine phosphatases. *Cancer Lett.* **110**, 49–55 (1996).
11. Zeng, Q. *et al.* Prenylation-dependent association of protein-tyrosine phosphatases PRL-1, -2, and -3 with the plasma membrane and the early endosome. *J. Biol. Chem.* **275**, 21444–21452 (2000).
12. Diamond, R. H., Cressman, D. E., Laz, T. M., Abrams, C. S. & Taub, R. PRL-1, a unique nuclear protein tyrosine phosphatase, affects cell growth. *Mol. Cell. Biol.* **14**, 3752–62 (1994).
13. Fagerli, U.-M. *et al.* Overexpression and involvement in migration by the metastasis-associated phosphatase PRL-3 in human myeloma cells. *Blood* **111**, 806–815 (2008).
14. Matter, W. F. *et al.* Role of PRL-3, a human muscle-specific tyrosine phosphatase, in angiotensin-II signalling. *Biochem. Biophys. Res. Commun.* **283**, 1061–8 (2001).
15. Sun, J.-P. *et al.* Phosphatase activity, trimerization, and the C-terminal polybasic region are all required for PRL1-mediated cell growth and migration. *J. Biol. Chem.* **282**, 29043–29051 (2007).
16. Fiordalisi, J. J., Keller, P. J. & Cox, A. D. PRL tyrosine phosphatases regulate rho family GTPases to promote invasion and motility. *Cancer Res.* **66**, 3153–61 (2006).
17. Song, R. *et al.* Phosphatase of regenerating liver-3 localizes to cyto-membrane and is required for B16F1 melanoma cell metastasis *in vitro* and *in vivo*. *PLoS One* **4**, e4450 (2009).
18. Foy, M., Anézo, O., Saule, S. & Planque, N. PRL-3 / PTP4A3 phosphatase regulates integrin β 1 in adhesion structures during migration of human ocular melanoma cells. *Exp. Cell Res.* **353**, 88–99 (2017).

19. Saha, S. A phosphatase associated with metastasis of colorectal cancer. *Science* (80-.). **294**, 1343–1346 (2001).
20. Miskad, U. A. *et al.* High PRL-3 expression in human gastric cancer is a marker of metastasis and grades of malignancies: an *in situ* hybridization study. *Virchows Arch.* **450**, 303–310 (2007).
21. Polato, F. *et al.* PRL-3 phosphatase is implicated in ovarian cancer growth. *Clin. Cancer Res.* **11**, 6835–9 (2005).
22. Ren, T. *et al.* Prognostic significance of phosphatase of regenerating liver-3 expression in ovarian cancer. *Pathol. Oncol. Res.* **15**, 555–560 (2009).
23. Ma, Y. & Li, B. Expression of phosphatase of regenerating liver-3 in squamous cell carcinoma of the cervix. *Med. Oncol.* **28**, 775–780 (2011).
24. Ming, J., Liu, N., Gu, Y., Qiu, X. & Wang, E.-H. PRL-3 facilitates angiogenesis and metastasis by increasing ERK phosphorylation and up-regulating the levels and activities of Rho-A/C in lung cancer. *Pathology* **41**, 118–26 (2009).
25. Xu, Y. *et al.* Expression and prognostic value of PRL-3 in Human intrahepatic cholangiocarcinoma. *Pathol. Oncol. Res.* **16**, 169–175 (2010).
26. Zhao, W.-B., Li, Y., Liu, X., Zhang, L.-Y. & Wang, X. Evaluation of PRL-3 expression, and its correlation with angiogenesis and invasion in hepatocellular carcinoma. *Int. J. Mol. Med.* **22**, 187–92 (2008).
27. Kong, L., Li, Q., Wang, L., Liu, Z. & Sun, T. The value and correlation between PRL-3 expression and matrix metalloproteinase activity and expression in human gliomas. *Neuropathology* **27**, 516–521 (2007).
28. Zhou, J., Wang, S., Lu, J., Li, J. & Ding, Y. Over-expression of phosphatase of regenerating liver-3 correlates with tumor progression and poor prognosis in nasopharyngeal carcinoma. *Int. J. Cancer* **124**, 1879–1886 (2009).

29. Liu, Y.-Q., Li, H.-X., Lou, X. & Lei, J.-Y. Expression of phosphatase of regenerating liver 1 and 3 mRNA in esophageal squamous cell carcinoma. *Arch. Pathol. Lab. Med.* **132**, 1307–12 (2008).
30. Buffart, T. E. *et al.* DNA copy number changes at 8q11-24 in metastasized colorectal cancer. *Cell. Oncol.* **27**, 57–65 (2005).
31. Bardelli, A. *et al.* PRL-3 expression in metastatic cancers. *Clin. Cancer Res.* **9**, 5607–15 (2003).
32. Radke, I. *et al.* Expression and prognostic impact of the protein tyrosine phosphatases PRL-1, PRL-2 and PRL-3 in breast cancer. *Br. J. Cancer* **95**, 347–354 (2006).
33. Laurent, C. *et al.* High PTP4A3 phosphatase expression correlates with metastatic risk in uveal melanoma patients. *Cancer Res.* **71**, 666–74 (2011).
34. Al-Aidaros, A. Q. O. & Zeng, Q. PRL-3 phosphatase and cancer metastasis. *J. Cell. Biochem.* **111**, 1087–1098 (2010).
35. Dong, Q., Ding, X., Chang, B., Wang, H. & Wang, A. PRL-3 promotes migration and invasion and is associated with poor prognosis in salivary adenoid cystic carcinoma. *J. Oral Pathol. Med.* **45**, 111–8 (2016).
36. Qu, S. *et al.* Independent oncogenic and therapeutic significance of phosphatase PRL-3 in FLT3-ITD-negative acute myeloid leukemia. *Cancer* **120**, 2130–2141 (2014).
37. Broyl, A. *et al.* Gene expression profiling for molecular classification of multiple myeloma in newly diagnosed patients. *Blood* **116**, 2543–2553 (2010).
38. Kondratova, M., Sompairac, N., Barillot, E., Zinovyev, A. & Kuperstein, I. Signalling maps in cancer research: construction and data analysis. *Database (Oxford)*. **2018**, (2018).
39. Kitano, H., Funahashi, A., Matsuoka, Y. & Oda, K. Using process diagrams for the graphical representation of biological networks. *Nat. Biotechnol.* **23**, 961–966 (2005).

40. Novère, N. Le *et al.* The Systems Biology Graphical Notation. *Nat. Biotechnol.* **27**, 735–741 (2009).
41. Hucka, M. *et al.* The systems biology markup language (SBML): a medium for representation and exchange of biochemical network models. *Bioinformatics* **19**, 524–31 (2003).
42. Vera-Licona, P., Bonnet, E., Barillot, E. & Zinovyev, A. OCSANA: optimal combinations of interventions from network analysis. *Bioinformatics* **29**, 1571–3 (2013).
43. Zinovyev, A., Viara, E., Calzone, L. & Barillot, E. BiNoM: a Cytoscape plugin for manipulating and analyzing biological networks. *Bioinformatics* **24**, 876–7 (2008).
44. Shannon, P. *et al.* Cytoscape: A software environment for integrated models of biomolecular interaction networks. *Genome Res.* **13**, 2498–2504 (2003).
45. Dorel, M., Viara, E., Barillot, E., Zinovyev, A. & Kuperstein, I. NaviCom: a web application to create interactive molecular network portraits using multi-level omics data. *Database (Oxford)*. **2017**, (2017).
46. Gawron, P. *et al.* MINERVA-a platform for visualization and curation of molecular interaction networks. *NPJ Syst. Biol. Appl.* **2**, 16020 (2016).
47. Pratt, D. *et al.* NDEx 2.0: A clearinghouse for research on cancer pathways. *Cancer Res.* **77**, e58–e61 (2017).
48. Basak, S. *et al.* The metastasis-associated gene Prl-3 is a p53 target involved in cell-cycle regulation. *Mol. Cell* **30**, 303–14 (2008).
49. Min, S.-H. *et al.* Downregulation of p53 by phosphatase of regenerating liver 3 is mediated by MDM2 and PIRH2. *Life Sci.* **86**, 66–72 (2010).
50. Xie, H. & Wang, H. PRL-3 promotes breast cancer progression by downregulating p14ARF-mediated p53 expression. *Oncol. Lett.* **15**, 2795–2800 (2017).
51. Lian, S. *et al.* PRL-3 activates NF- κ B signalling pathway by interacting with RAP1.

- Biochem. Biophys. Res. Commun.* **430**, 196–201 (2013).
52. Lai, W. *et al.* PRL-3 promotes the proliferation of LoVo cells via the upregulation of KCNN4 channels. *Oncol. Rep.* **26**, 909–17 (2011).
 53. Gari, H. H., DeGala, G. D., Lucia, M. S. & Lambert, J. R. Loss of the oncogenic phosphatase PRL-3 promotes a TNF-R1 feedback loop that mediates triple-negative breast cancer growth. *Oncogenesis* **5**, e255 (2016).
 54. Wang, L. *et al.* PTP4A3 is a target for inhibition of cell proliferation, migration and invasion through Akt/mTOR signalling pathway in glioblastoma under the regulation of miR-137. *Brain Res.* **1646**, 441–50 (2016).
 55. Ye, Z. *et al.* PRL-3 activates mTORC1 in cancer progression. *Sci. Rep.* **5**, 17046 (2015).
 56. Zhou, J. *et al.* A loss-of-function genetic screening reveals synergistic targeting of AKT/mTOR and WTN/ β -catenin pathways for treatment of AML with high PRL-3 phosphatase. *J. Hematol. Oncol.* **11**, 36 (2018).
 57. Sun, Z.-H. & Bu, P. Downregulation of phosphatase of regenerating liver-3 is involved in the inhibition of proliferation and apoptosis induced by emodin in the SGC-7901 human gastric carcinoma cell line. *Exp. Ther. Med.* **3**, 1077–1081 (2012).
 58. Al-Aidaros, A. Q. O. *et al.* Metastasis-associated PRL-3 induces EGFR activation and addiction in cancer cells. *J. Clin. Invest.* **123**, 3459–71 (2013).
 59. Slørdahl, T. S. *et al.* The phosphatase of regenerating liver-3 (PRL-3) is important for IL-6-mediated survival of myeloma cells. *Oncotarget* **7**, 27295–306 (2016).
 60. Zhang, J. *et al.* miR-21, miR-17 and miR-19a induced by phosphatase of regenerating liver-3 promote the proliferation and metastasis of colon cancer. *Br. J. Cancer* **107**, 352–9 (2012).
 61. Guo, K. *et al.* PRL-3 initiates tumor angiogenesis by recruiting endothelial cells *in vitro* and *in vivo*. *Cancer Res.* **66**, 9625–35 (2006).

62. Xu, J. *et al.* VEGF promotes the transcription of the human PRL-3 gene in HUVEC through transcription factor MEF2C. *PLoS One* **6**, e27165 (2011).
63. Zimmerman, M. W. *et al.* Protein-tyrosine phosphatase 4A3 (PTP4A3) promotes vascular endothelial growth factor signalling and enables endothelial cell motility. *J. Biol. Chem.* **289**, 5904–13 (2014).
64. Ming, J., Jiang, Y., Jiang, G. & Zheng, H. Phosphatase of regenerating liver-3 induces angiogenesis by increasing extracellular signal-regulated kinase phosphorylation in endometrial adenocarcinoma. *Pathobiology* **81**, 1–7 (2014).
65. Peng, L. *et al.* Identification of integrin alpha1 as an interacting protein of protein tyrosine phosphatase PRL-3. *Biochem. Biophys. Res. Commun.* **342**, 179–83 (2006).
66. Peng, L. *et al.* PRL-3 promotes the motility, invasion, and metastasis of LoVo colon cancer cells through PRL-3-integrin beta1-ERK1/2 and-MMP2 signalling. *Mol. Cancer* **8**, 110 (2009).
67. Tian, W. *et al.* Phosphatase of regenerating liver-3 directly interacts with integrin β 1 and regulates its phosphorylation at tyrosine 783. *BMC Biochem.* **13**, 22 (2012).
68. Liu, H. *et al.* PRL-3 suppresses c-Fos and integrin α 2 expression in ovarian cancer cells. *BMC Cancer* **13**, 80 (2013).
69. Wang, H. *et al.* PRL-3 down-regulates PTEN expression and signals through PI3K to promote epithelial-mesenchymal transition. *Cancer Res.* **67**, 2922–6 (2007).
70. Krndija, D. *et al.* The phosphatase of regenerating liver 3 (PRL-3) promotes cell migration through Arf-activity-dependent stimulation of integrin α 5 recycling. *J. Cell Sci.* **125**, 3883–92 (2012).
71. Lian, S. *et al.* PRL-3 promotes cell adhesion by interacting with JAM2 in colon cancer. *Oncol. Lett.* **12**, 1661–1666 (2016).
72. Hjort, M. A. *et al.* Phosphatase of regenerating liver-3 is expressed in acute

- lymphoblastic leukemia and mediates leukemic cell adhesion, migration and drug resistance. (2017). at <www.impactjournals.com/oncotarget>
73. McParland, V. *et al.* The metastasis-promoting phosphatase PRL-3 shows activity toward phosphoinositides. *Biochemistry* **50**, 7579–90 (2011).
 74. Cao, Y. *et al.* RNAi-mediated knockdown of PRL-3 inhibits cell invasion and downregulates ERK 1/2 expression in the human gastric cancer cell line, SGC-7901. *Mol. Med. Rep.* **7**, 1805–11 (2013).
 75. Forte, E. *et al.* Ezrin is a specific and direct target of protein tyrosine phosphatase PRL-3. *Biochim. Biophys. Acta* **1783**, 334–44 (2008).
 76. Mizuuchi, E., Semba, S., Kodama, Y. & Yokozaki, H. Down-modulation of keratin 8 phosphorylation levels by PRL-3 contributes to colorectal carcinoma progression. *Int. J. Cancer* **124**, 1802–10 (2009).
 77. Zheng, P. *et al.* Stathmin, a new target of PRL-3 identified by proteomic methods, plays a key role in progression and metastasis of colorectal cancer. *J. Proteome Res.* **9**, 4897–905 (2010).
 78. Fiordalisi, J. J., Dewar, B. J., Graves, L. M., Madigan, J. P. & Cox, A. D. Src-mediated phosphorylation of the tyrosine phosphatase PRL-3 is required for PRL-3 promotion of Rho activation, motility and invasion. *PLoS One* **8**, e64309 (2013).
 79. ZHANG, P. *et al.* Expression and its relationship of PRL-3 and RhoC in non-small cell lung cancer. *Chinese J. Lung Cancer* **13**, 598–601 (2010).
 80. Maacha, S. *et al.* Protein tyrosine phosphatase 4A3 (PTP4A3) is required for *Xenopus laevis* cranial neural crest migration in vivo. *PLoS One* **8**, e84717 (2013).
 81. Xiong, J. *et al.* PRL-3 promotes the peritoneal metastasis of gastric cancer through the PI3K/Akt signalling pathway by regulating PTEN. *Oncol. Rep.* **36**, 1819–28 (2016).
 82. Ren, S. *et al.* PRL-3 is involved in estrogen- and IL-6-induced migration of endometrial

stromal cells from ectopic endometrium. *Reprod. Sci.* (2016).
doi:10.1177/1933719116650751

83. Jiang, Y. *et al.* Phosphatase PRL-3 is a direct regulatory target of TGFbeta in colon cancer metastasis. *Cancer Res.* **71**, 234–44 (2011).
84. Huang, Y.-H. *et al.* A role of autophagy in PTP4A3-driven cancer progression. *Autophagy* **10**, 1–14 (2014).
85. Liu, Y. *et al.* PRL-3 promotes epithelial mesenchymal transition by regulating cadherin directly. *Cancer Biol. Ther.* **8**, 1352–9 (2009).
86. Pryczynicz, A., Guzińska-Ustymowicz, K., Niewiarowska, K., Cepowicz, D. & Kemon, A. PRL-3 and E-cadherin show mutual interactions and participate in lymph node metastasis formation in gastric cancer. *Tumor Biol.* **35**, 6587–92 (2014).
87. Fang, X.-Y. *et al.* PRL-3 promotes the malignant progression of melanoma via triggering dephosphorylation and cytoplasmic localization of NHERF1. *J. Invest. Dermatol.* **135**, 2273–82 (2015).
88. Lai, W. *et al.* KCNN4 channels participate in the EMT induced by PRL-3 in colorectal cancer. *Med. Oncol.* **30**, 566 (2013).
89. Chong, P. S. Y. *et al.* LEO1 is regulated by PRL-3 and mediates its oncogenic properties in acute myelogenous leukemia. *Cancer Res.* **74**, 3043–53 (2014).
90. Liang, F. *et al.* PRL3 promotes cell invasion and proliferation by down-regulation of Csk leading to Src activation. *J. Biol. Chem.* **282**, 5413–9 (2007).
91. Liang, F. *et al.* Translational control of C-terminal Src kinase (Csk) expression by PRL3 phosphatase. *J. Biol. Chem.* **283**, 10339–46 (2008).
92. Walls, C. D. *et al.* Phosphatase of regenerating liver 3 (PRL3) provokes a tyrosine phosphoproteome to drive prometastatic signal transduction. *Mol. Cell. Proteomics* **12**, 3759–3777 (2013).

93. Gari, H. H., DeGala, G. D., Ray, R., Lucia, M. S. & Lambert, J. R. PRL-3 engages the focal adhesion pathway in triple-negative breast cancer cells to alter actin structure and substrate adhesion properties critical for cell migration and invasion. *Cancer Lett.* **380**, 505–512 (2016).
94. Lee, S.-K. *et al.* Phosphatase of regenerating liver-3 promotes migration and invasion by upregulating matrix metalloproteinases-7 in human colorectal cancer cells. *Int. J. Cancer* **131**, E190-203 (2012).
95. Mu, N. *et al.* PRL-3 is a potential glioblastoma prognostic marker and promotes glioblastoma progression by enhancing MMP7 through the ERK and JNK pathways. *Theranostics* **8**, 1527–1539 (2018).
96. Maacha, S. *et al.* Protein tyrosine phosphatase 4A3 (PTP4A3) promotes human uveal melanoma aggressiveness through membrane accumulation of matrix metalloproteinase 14 (MMP14). *Investig. Ophthalmol. Vis. Sci.* **57**, 1982–1990 (2016).
97. Lan, Q. *et al.* CCL26 Participates in the PRL-3-induced promotion of colorectal cancer invasion by stimulating tumor-associated macrophage infiltration. *Mol. Cancer Ther.* **17**, 276–289 (2018).
98. Sica, A. & Bronte, V. Altered macrophage differentiation and immune dysfunction in tumor development. *J. Clin. Invest.* **117**, 1155–66 (2007).
99. Kuperstein, I. *et al.* Atlas of Cancer Signalling Network: a systems biology resource for integrative analysis of cancer data with Google Maps. *Oncogenesis* **4**, e160 (2015).
100. Monraz Gomez, L. C. *et al.* Application of Atlas of Cancer Signalling Network in preclinical studies. *Brief. Bioinform.* (2018). doi:10.1093/bib/bby031
101. Mazein, A. *et al.* Systems medicine disease maps: community-driven comprehensive representation of disease mechanisms. *npj Syst. Biol. Appl.* **4**, 21 (2018).
102. Ostaszewski, M. *et al.* Community-driven roadmap for integrated disease maps. *Brief.*

Acknowledgements

We thank Nicolas Sompairac for help with the generation of online maps with the NaviCell, MINERVA and NDex platforms. This work was supported by COLOSYS grant ANR-15-CMED-0001-04, provided by the *Agence Nationale de la Recherche* under the frame of ERACoSysMed-1, the ERA-Net for Systems Medicine in clinical research and medical practice, a PRECISE H2020 EU grant and a Retina France grant. This work received support from the MASTODON program from the CNRS (project APLIGOOGL).

Authors' contributions

LD, reviewed the literature, constructed signalling network map and wrote the paper. LCMG, performed structural analysis of the signalling network map, created reduced models and wrote the paper. IK, supervised the systems biology part of the work and coordinated the writing of the paper. SS, leaded the PRL-3-related project, advised during the writing of the paper and critically revised the text.

Competing interest

The authors have no potential conflicts of interest

Figure legends

Figure 1. A: Molecular mechanisms induced by PRL-3 leading to cell cycle progression, survival and proliferation in cancer. B: Molecular mechanisms leading to angiogenesis induced by PRL-3 in cancer.

Figure 2. A: Molecular mechanisms of cell matrix adhesion induced by PRL-3 in cancer. B: Molecular mechanism of cytoskeleton remodelling induced by PRL-3 in cancer. For the annotations, please see the legend to Figure 1.

Figure 3. A: Molecular mechanisms leading to EMT and motility induced by PRL-3 in cancer. B: Molecular mechanisms that promote invasion induced by PRL-3 in cancer. For the annotations, please see the legend to Figure 1.

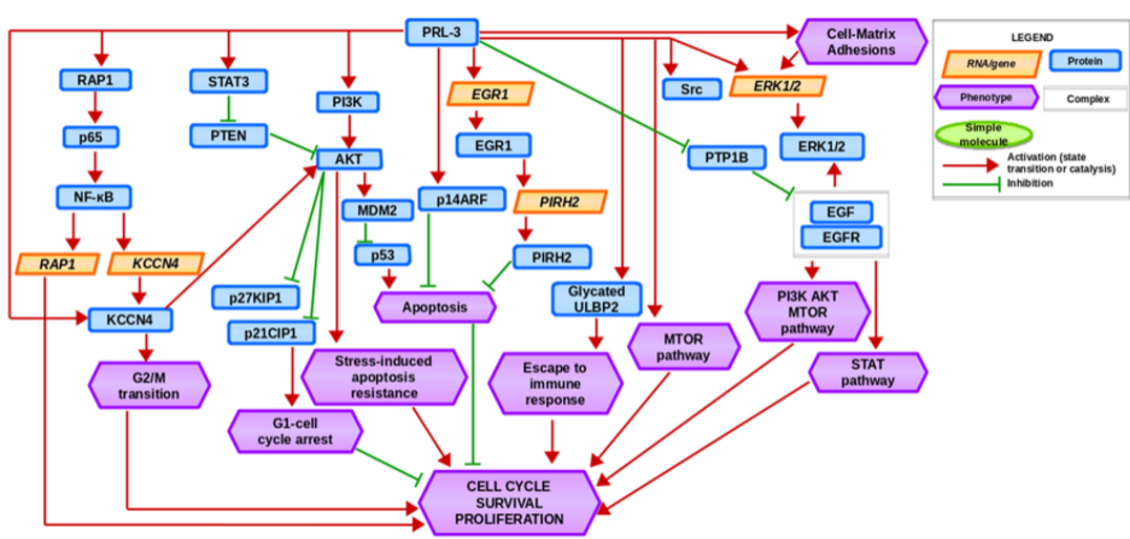
Figure 4. Main players and signalling pathways regulated by PRL-3 in the key steps in the processes of tumorigenesis and metastasis.

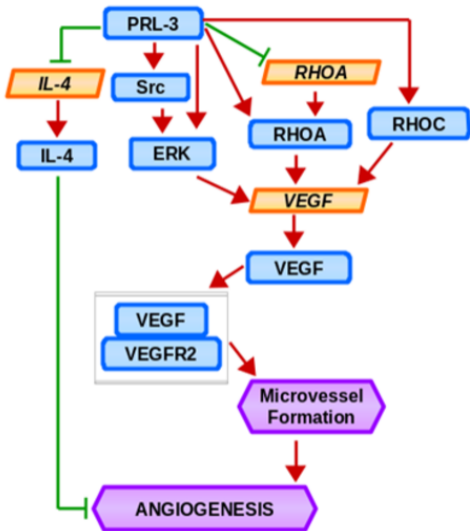
Supplementary materials

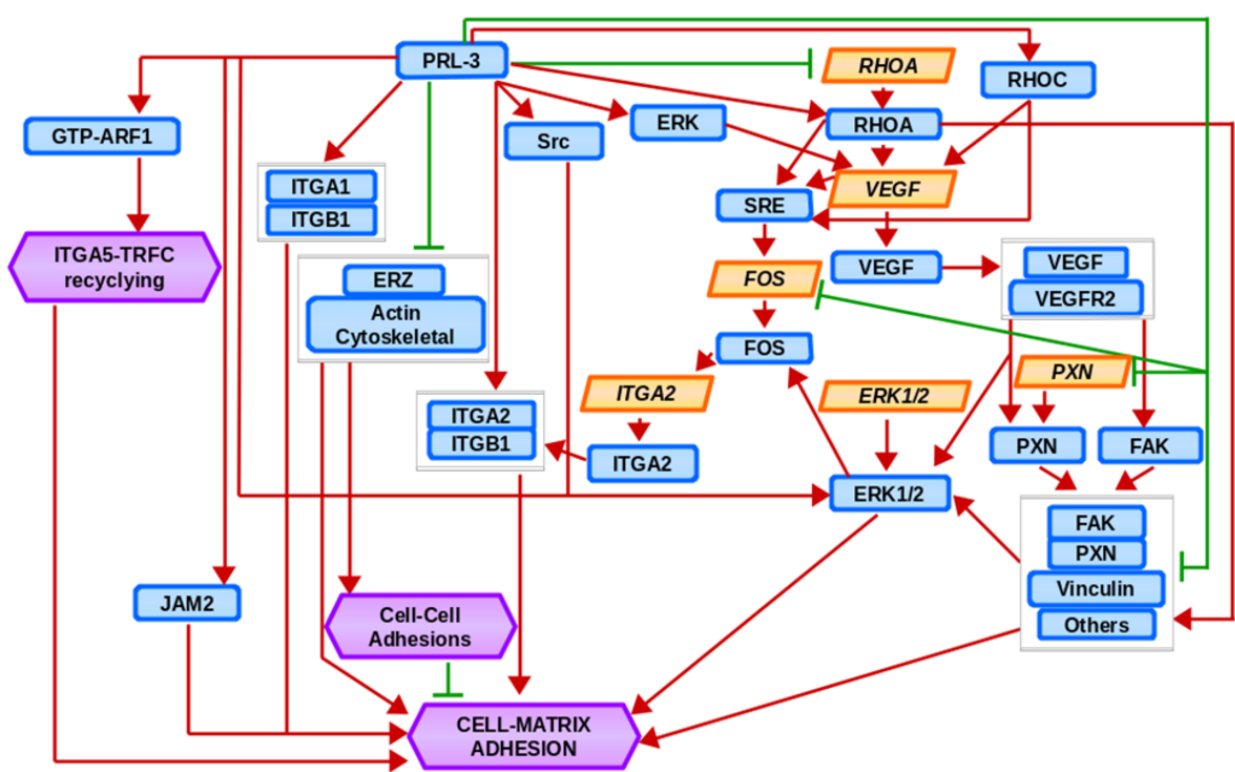
Supplementary Figure 1: Comprehensive signalling network map for PRL-3 involvement in cancer and metastasis. The network was manually constructed in CellDesigner. It covers 117 proteins, represents 364 reactions and is based on 63 scientific papers. The background colour highlight the borders of functional modules. The maps are open-source and available from three web-based platforms for exploration and analysis.

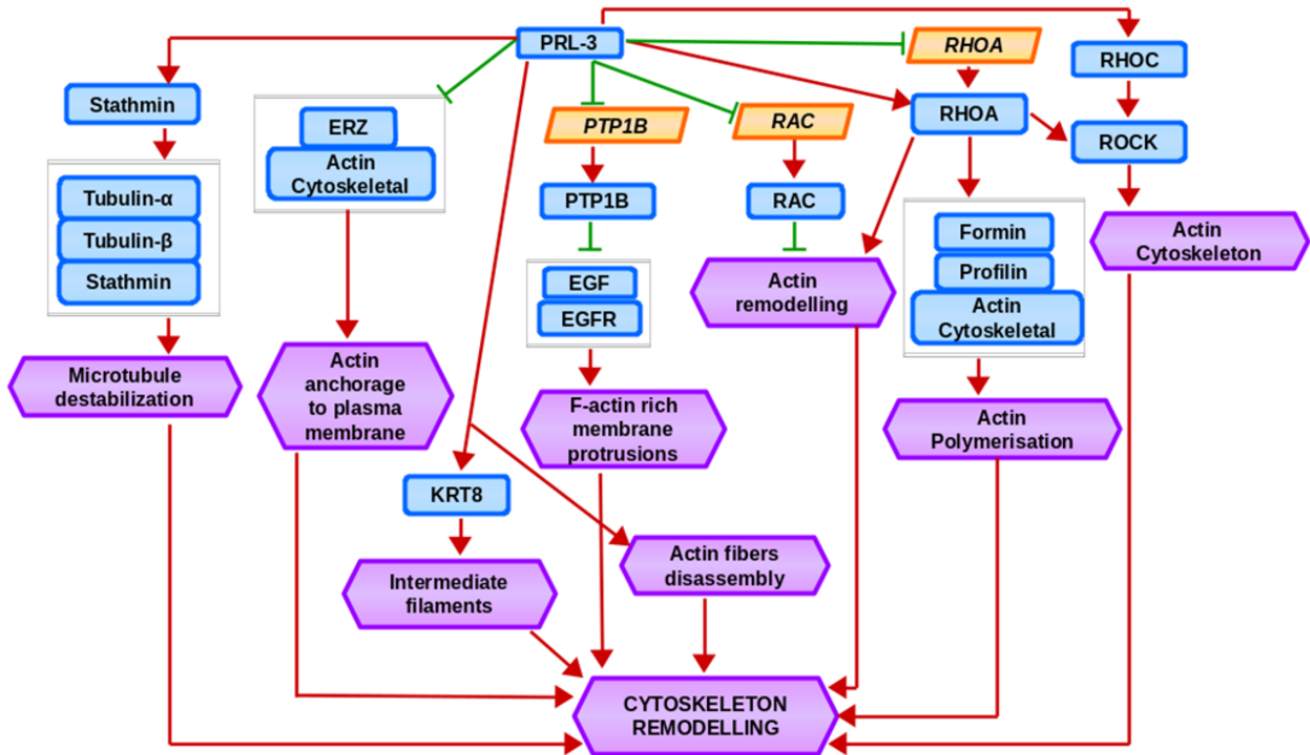
Supplementary Figure 2: Map entity annotation page in NaviCell format. The annotation of each entity can be accessed via the call out window by clicking on the marker near the entity of interest. The annotation of each entity contains active links to identifiers; tags of modules in which the entity participates (clickable globe symbol leads to the corresponding module map) and links to the supporting references.

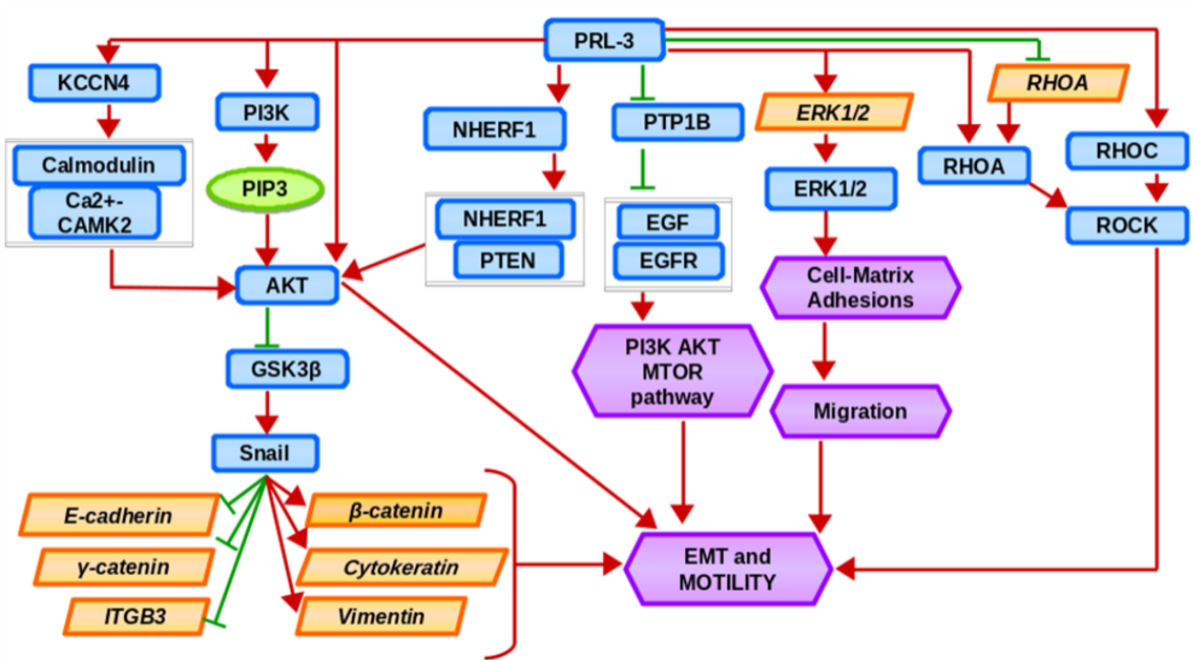
Supplementary Figure 3: EMT and Motility module, corresponding to the model diagram in Figure 3A. The maps are open-source and available from three web-based platforms for exploration and analysis.











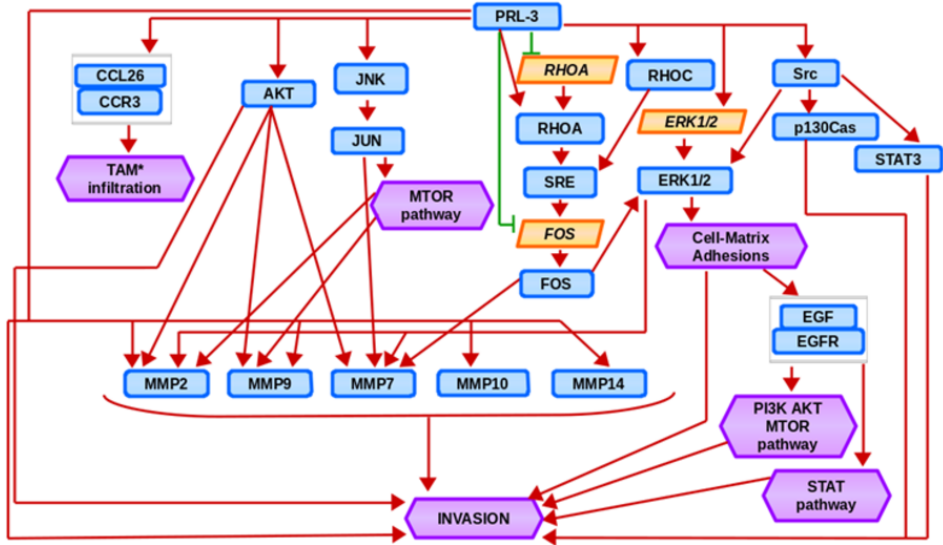


Figure 4

