

5-1-2011

## Mitostatin is down-regulated in human prostate cancer and suppresses the invasive phenotype of prostate cancer cells.

Matteo Fassan

*Department of Urology, Kimmel Cancer Center, Thomas Jefferson University, Philadelphia, Pennsylvania;  
Department of Diagnostic Medicine and Special Therapies, University of Padova, Padova, Italy*

Domenico D'Arca

*Department of Urology, Kimmel Cancer Center, Thomas Jefferson University, Philadelphia, Pennsylvania*

Juraj Letko

*Department of Urology, Kimmel Cancer Center, Thomas Jefferson University, Philadelphia, Pennsylvania*

Andrea Vecchione

*Department of Urology, Kimmel Cancer Center, Thomas Jefferson University, Philadelphia, Pennsylvania;  
Division of Pathology, II Faculty of Medicine, University "La Sapienza," Ospedale Sant'Andrea, Rome, Italy,  
Part of the Medical Cell Biology Commons, Medical Pathology Commons, Oncology Commons, and  
the Urology Commons*

Andrea.Vecchione@mail.tju.edu

Marina P Gardiman

*Department of Diagnostic Medicine and Special Therapies, University of Padova, Padova, Italy*

### Recommended Citation

*See next page for additional authors*

Fassan, Matteo, D'Arca, Domenico, Letko, Juraj; Vecchione, Andrea; Gardiman, Marina P; McCue, Peter; Wildemore, Bernadette; Rugge, Massimo; Shupp-Byrne, Dolores; Gomella, Leonard G; Morrione, Andrea; Iozzo, Renato V; and Baffa, Raffaele, "Mitostatin is down-regulated in human prostate cancer and suppresses the invasive phenotype of prostate cancer cells." (2011). *Kimmel Cancer Center Faculty Papers*. Paper 5.

<https://jdc.jefferson.edu/kimmelccfp/5>

This Article is brought to you for free and open access by the Jefferson Digital Commons. The Jefferson Digital Commons is a service of Thomas Jefferson University's [Center for Teaching and Learning \(CTL\)](#). The Commons is a showcase for Jefferson books and journals, peer-reviewed scholarly publications, unique historical collections from the University archives, and teaching tools. The Jefferson Digital Commons allows researchers and interested readers anywhere in the world to learn about and keep up to date with Jefferson scholarship. This article has been accepted for inclusion in Kimmel Cancer Center Faculty Papers by an authorized administrator of the Jefferson Digital Commons. For more information, please contact: [JeffersonDigitalCommons@jefferson.edu](mailto:JeffersonDigitalCommons@jefferson.edu).

---

## Authors

Matteo Fassan, Domenico D'Arca, Juraj Letko, Andrea Vecchione, Marina P Gardiman, Peter McCue, Bernadette Wildemore, Massimo Rugge, Dolores Shupp-Byrne, Leonard G Gomella, Andrea Morrione, Renato V Iozzo, and Raffaele Baffa

# Mitostatin Is Down-Regulated in Human Prostate Cancer and Suppresses the Invasive Phenotype of Prostate Cancer Cells

Matteo Fassan<sup>1,3</sup>, Domenico D'Arca<sup>1</sup>, Juraj Letko<sup>1</sup>, Andrea Vecchione<sup>1,4</sup>, Marina P. Gardiman<sup>3</sup>, Peter McCue<sup>2</sup>, Bernadette Wildemore<sup>2</sup>, Massimo Rugge<sup>3</sup>, Dolores Shupp-Byrne<sup>1</sup>, Leonard G. Gomella<sup>1</sup>, Andrea Morrione<sup>1</sup>, Renato V. Iozzo<sup>2</sup>, Raffaele Baffa<sup>1\*†</sup>

**1** Department of Urology, Kimmel Cancer Center, Thomas Jefferson University, Philadelphia, Pennsylvania, United States of America, **2** Department of Pathology, Anatomy and Cell Biology, Kimmel Cancer Center, Thomas Jefferson University, Philadelphia, Pennsylvania, United States of America, **3** Department of Diagnostic Medicine and Special Therapies, University of Padova, Padova, Italy, **4** Division of Pathology, II Faculty of Medicine, University "La Sapienza," Ospedale Sant'Andrea, Rome, Italy

## Abstract

*MITOSTATIN*, a novel putative tumor suppressor gene induced by decorin overexpression, is expressed in most normal human tissues but is markedly down-regulated in advanced stages of mammary and bladder carcinomas. Mitostatin negatively affects cell growth, induces cell death and regulates the expression and activation levels of Hsp27. In this study, we demonstrated that ectopic expression of Mitostatin in PC3, DU145, and LNCaP prostate cancer cells not only induced a significant reduction in cell growth, but also inhibited migration and invasion. Moreover, Mitostatin inhibited colony formation in soft-agar of PC3 and LNCaP cells as well as tumorigenicity of LNCaP cells in nude mice. Conversely, targeting endogenous Mitostatin by siRNA and anti-sense strategies in PC3 and DU145 prostate cancer cells enhanced the malignant phenotype in both cell lines. In agreement of these anti-oncogenic roles, we discovered that Mitostatin was absent in ~35% ( $n = 124$ ) of prostate tumor samples and its overall reduction was associated with advanced cancer stages. Collectively, our findings indicate that *MITOSTATIN* may act as a tumor suppressor gene in prostate cancer and provide a novel cellular and molecular mechanism to be further exploited and deciphered in our understanding of prostate cancer progression.

**Citation:** Fassan M, D'Arca D, Letko J, Vecchione A, Gardiman MP, et al. (2011) Mitostatin Is Down-Regulated in Human Prostate Cancer and Suppresses the Invasive Phenotype of Prostate Cancer Cells. PLoS ONE 6(5): e19771. doi:10.1371/journal.pone.0019771

**Editor:** Hava Karsenty Avraham, Beth Israel Deaconess Medical Center, United States of America

**Received:** January 31, 2011; **Accepted:** April 4, 2011; **Published:** May 6, 2011

**Copyright:** © 2011 Fassan et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

**Funding:** This work was in part supported by the Sidney Kimmel Foundation for Cancer Research, the Benjamin Perkins Bladder Cancer Fund and the Martin Greitzer Fund (to R.B.), the National Institutes of Health grants RO1 CA39481, RO1 CA47282 and RO1 CA120975 (to R.V.I.), RO1 DK068419 (to A.M.). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

**Competing Interests:** The authors have declared that no competing interests exist.

\* E-mail: R\_Baffa@mail.jci.tju.edu

† Current address: Global Oncology Division, Sanofi-Aventis, Cambridge, Massachusetts, United States of America

## Introduction

Prostate cancer is the main cause of cancer-related death in men in most developed countries, and the most common malignancy in American males. In the United States, one over eight men will develop prostate cancer during his life and over 27,360 men are expected to die from the disease this year [1].

Molecular genetics studies of prostate cancer have identified mutations, deletions, or loss of tumor suppressor genes expression in subsets of patients with prostate cancer [2]. However, due to the heterogeneity of prostate cancer itself and the focal nature of oncogene/tumor suppressor gene alterations, the role of these genes in prostate cancer onset and the diagnostic and/or prognostic value of such genes alterations remains uncertain [2].

Loss of heterozygosity (LOH) points out the presence of suppressor genes at specific chromosomal regions in tumors. Several allelotyping studies reported the telomeric portion of chromosome 12 to be deleted in a variety of solid tumors [3–11], including prostate cancer [12].

*MITOSTATIN* is a novel putative tumor suppressor gene localized at 12q24.1 [13–15] recently characterized in our

laboratory [13]. We have previously demonstrated that this decorin-induced 62-kDa protein is expressed in most human tissues; it affects prostate cancer cell growth and cell death by regulating the level and activation of Hsp27 [13]. We have also analyzed by immunohistochemistry the expression of Mitostatin in a series of primary bladder and breast tumors, and observed a reduction of Mitostatin protein levels in advanced tumor stages. In addition, Kim and colleagues have recently identified a frameshift mutation of *MITOSTATIN* gene in a gastric carcinoma with microsatellite instability [14].

Although the biological function of Mitostatin in prostate cancers is not yet characterized, its relationship to decorin and Hsp27 suggests a role for Mitostatin in cancer development. To study the tumor suppressor function of Mitostatin in prostate cancer, we over-expressed and depleted endogenous Mitostatin protein by antisense and siRNA strategies in prostate cancer-derived cell lines.

In this study, we provide the first evidence for a role of Mitostatin in inhibiting cell migration, invasion and tumorigenicity of prostate cancer cells. Furthermore, our data indicate that Mitostatin is down-regulated in advanced stage human prostate

cancers. Thus, Mitostatin could act as a classical tumor suppressor gene and analysis of its expression may prove a useful clinical marker for diagnosis and prognosis in this common human cancer.

## Results

### Mitostatin Over-expression in Prostate Cancer Cells Inhibits Colony Formation

As an initial approach to establish Mitostatin expression in prostate we utilized cell extracts from fourteen different prostate-derived cells, including both normal and malignant prostatic cells. Using immunoblotting with a Mitostatin-specific antibody [13], we discovered that all cell lines analyzed, but one (*i.e.*: 1542CP<sub>3</sub>TX), expressed Mitostatin protein at various levels (Figure 1A). Notably, LNCaP cells displayed the highest expression and 1532CP<sub>2</sub>TX showed a barely-detectable levels of endogenous Mitostatin (Figure 1A). Of note, 1542NPTX cells, which express Mitostatin, are the “normal” counterparts of the Mitostatin-negative malignant 1542CP<sub>3</sub>TX cells.

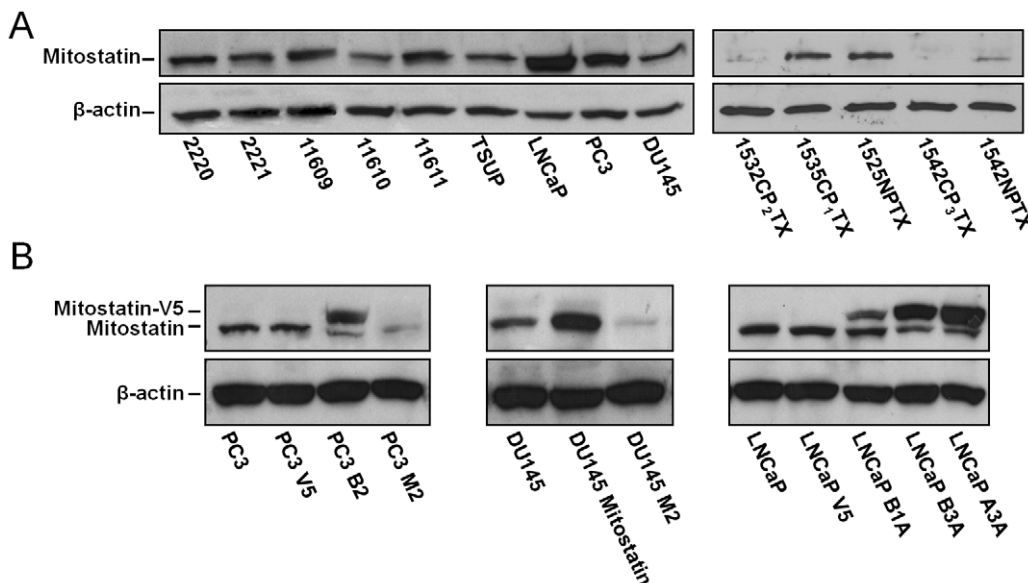
Next, we focused on investigating the biological function of Mitostatin in prostate cancer cells by stably transfecting PC3 and LNCaP cells with a V5-tagged Mitostatin cDNA expression construct and PC3 and DU145 cells with an anti-sense cDNA construct. We also placed the Mitostatin coding sequence in a self-inactivating retroviral vector under the control of an inducible *Drosophila* HPS70 promoter to infect DU145 cells. We obtained five clones stably over-expressing Mitostatin (PC3 B2, DU145 Mitostatin, LNCaP B1A, LNCaP B3A and LNCaP A3A) and two clones which showed decreased levels of endogenous Mitostatin protein (PC3 M2 and DU145 M2) (Figure 1B). In three independent colony formation assays, all Mitostatin-overexpressing cell lines showed a decrease in the number and size of colonies after 15 days (Figure 2 A–C) as compared to either the parental or the V5-transfected cells. DU145 Mitostatin, which is also the clone with the highest expression of Mitostatin compared to parental cell expression (4.2 fold increase, *cf* Figure 1B), showed the highest inhibition of colony formation (Figure 2 B). Of interest, cells

expressing a Mitostatin antisense construct showed either a similar (DU145 M2, Figure 2 B) or higher (PC3 M2, Figure 2A) number of colonies in comparison to the parental or mock transfected cells.

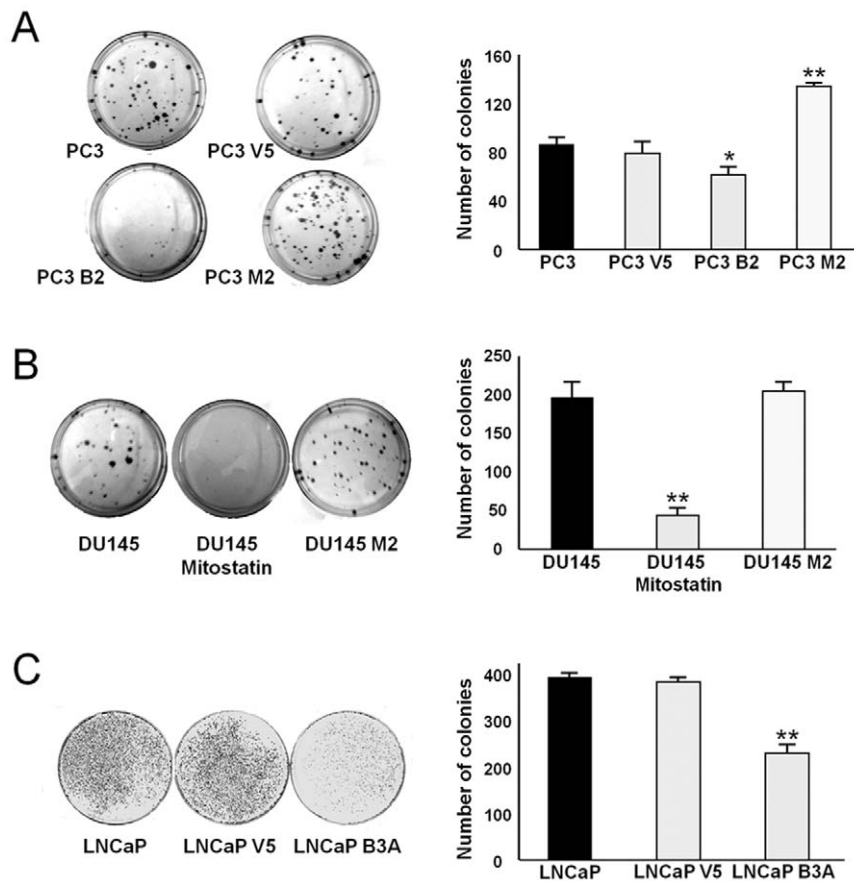
### Mitostatin Over-expression Inhibits Migration of Prostate Cancer Cells

It is well established that decorin and Hsp27 are involved in cell migration. The former has been shown to exert an anti-migratory effect in various cell lines involving different signaling pathways [16–19], whereas the latter is involved in the actin reorganization when cells form lamellipodia [20]. Since we have previously discovered Mitostatin in decorin-over-expressing cells and demonstrated that Mitostatin inhibits the expression and phosphorylation of Hsp27 in prostate cancer cell lines [13], we sought to determine whether Mitostatin may regulate cell migration in prostate cancer cells. Consequently, we conducted *in vitro* migration assays using the various Mitostatin-overexpressing or Mitostatin-depleted prostate cancer cells. In all cell line tested, Mitostatin over-expression inhibited the ability of cells to migrate (Figure 3A) indicating that Mitostatin negatively regulates migration of prostate cancer cells. In Mitostatin-over-expressing LNCaP clones the inhibitory effect of Mitostatin on migration was directly correlated to the amount of protein (*i.e.*: LNCaP A3A clone with the highest Mitostatin expression was the slowest in the migration assay). Conversely, prostate cancer cells in which endogenous Mitostatin was down-regulated by either antisense strategy (PC3 M2 and DU145 M2) or Mitostatin siRNA (PC3 cells) showed increased cell motility (Figures 3A).

Next, we determined the ability of Mitostatin to inhibit migration of prostate cancer cells using an *in vitro* “wound-healing” motility assay [21]. In contrast to parental cells and PC3 V5 control cells (data not shown), PC3 B2 cells over-expressing Mitostatin showed a substantial decrease in migration into the denuded area, both at 4 and 8 hours after the wounding (Figure 3B). We performed the same experiment on LNCaP and DU145 cells and observed that in all cell lines. Essentially,



**Figure 1. Mitostatin expression in prostate cancer cell lines.** **A:** Western blot analysis: Mitostatin is differentially expressed in human prostate cancer cell lines. Protein loading was confirmed by reprobing the membrane with antibody to  $\beta$ -actin. **B:** Western blots showing the expression of Mitostatin in PC3, DU145 and LNCaP cell lines utilized in this study. doi:10.1371/journal.pone.0019771.g001



**Figure 2. Mitostatin expression affects colony formation of prostate cancer cells.** Mitostatin over-expression in prostate cancer derived cell lines [PC3, **A**; DU145, **B**; and LNCaP, **C**] decreased the ability to form colonies after 15 days, while cells with depletion of endogenous Mitostatin protein showed a similar (DU145 M2) or higher (PC3 M2) number of colonies compared to parental cells. Columns, average per dish from triplicate experiments; bars, SEM. \*  $P < 0.05$ ; \*\*  $P < 0.01$ . doi:10.1371/journal.pone.0019771.g002

Mitostatin over-expression induced a decrease in cell motility compared to parental or mock-transfected cells (data not shown).

### Mitostatin Over-expression Inhibits Invasion and Cell Adhesion

The acquisition by cancer cells of an invasive phenotype is a critical step for tumor progression. Matrigel-coated filters are widely used to examine invasive migration through a three-dimensional extracellular matrix [21]. Consequently, we conducted *in vitro* invasion assays evaluating the ability of prostate cancer cells to invade through Matrigel in 5% serum-containing medium. Mitostatin over-expression inhibited cellular invasion in all cell lines tested (Figure 4A). In LNCaP over-expressing clones the inhibitory effect of the protein on migration was directly correlated to the amount of protein (LNCaP A3A had the lowest capability to invade). Moreover, we observed an increased in cell invasion in PC3 M2 and DU145 M2 antisense clones, and PC3 Mitostatin siRNA cells.

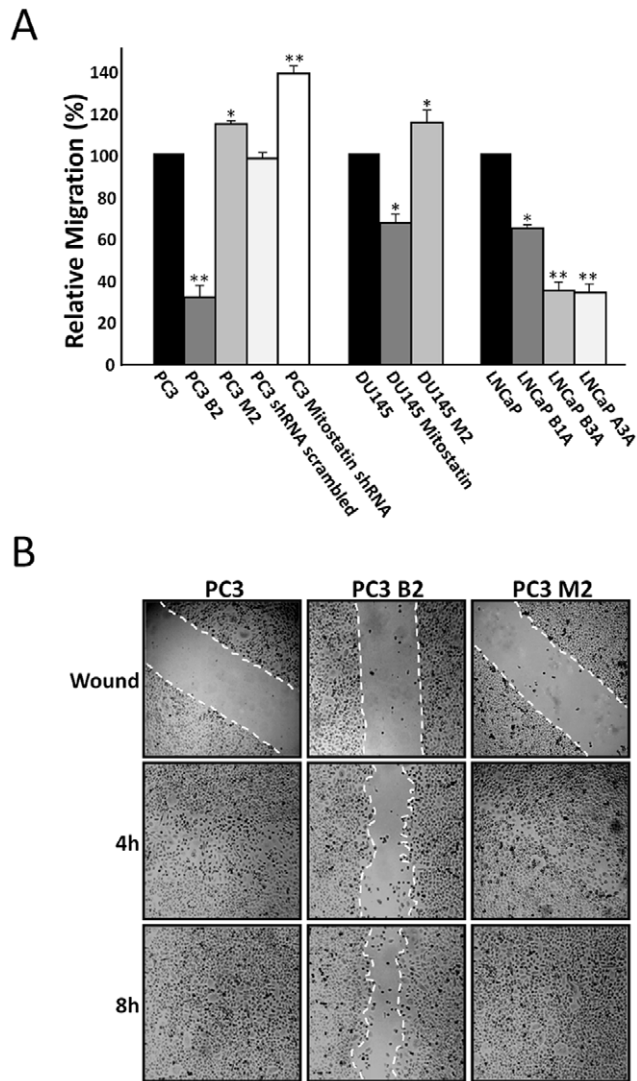
Adherence to extracellular matrix is an intrinsic characteristic of an invasive and metastatic phenotype and migrating cells form transient attachments to the extracellular matrix. Notably, laminin-1 is the major component of Matrigel. Therefore, we performed adhesion assays and plated the various Mitostatin-overexpressing or Mitostatin-depleted prostate cancer cells on laminin-coated plates. Cells were allowed to adhere to laminin for 2 hours and the number of attached cells was then calculated. The

number of cells that adhered to laminin was significantly lower in cells over-expressing Mitostatin as compared to parental cells in DU145 and PC3 cell lines (Figure 4B), indicating that Mitostatin inhibits cell adhesion to laminin. In agreement with this conclusion, Mitostatin-depleted PC3 cells showed an increased capacity to adhere to laminin (Figure 4B). On the other hand, the lack of significant differences in cell adhesion to laminin observed in the LNCaP cells could be partly explained by their documented low adhesive ability *in vitro* [22,23].

Collectively, our results suggest that Mitostatin not only inhibits the migratory ability of prostatic cancer cells but also the ability to invade a complex three-dimensional matrix, such as Matrigel, and to adhere to laminin substrata.

### Mitostatin Over-expression Inhibits Anchorage-independent Growth and Tumorigenicity

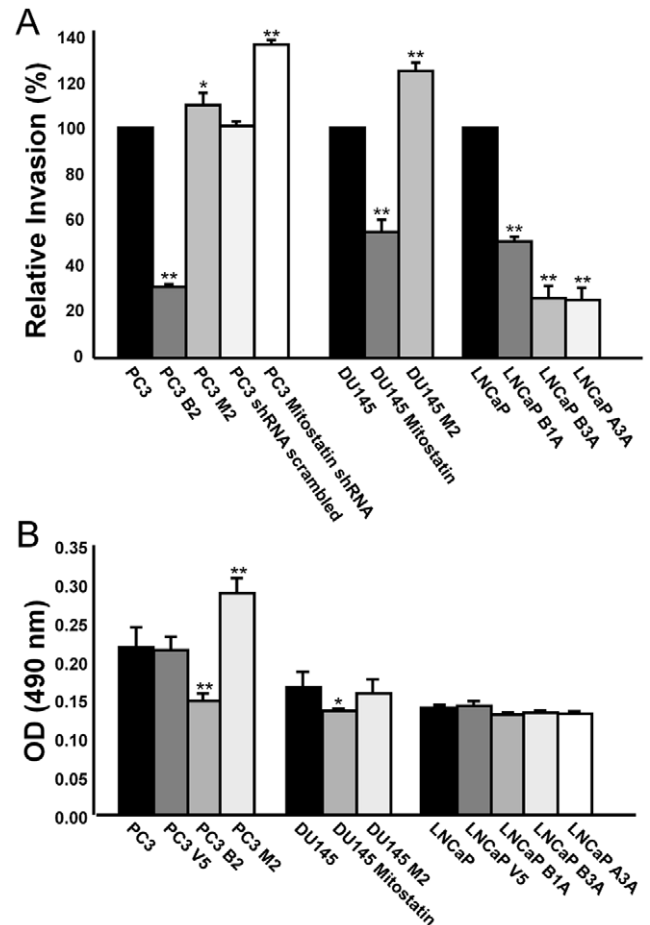
To further investigate the hypothesis that Mitostatin may play a direct role in prostate carcinogenesis, we performed anchorage-independent growth assays and an *in vivo* tumorigenicity assays in nude mice. PC3 B2 cells with high Mitostatin expression did not form colonies, whereas PC3 M2 with low Mitostatin level showed an increased number of colonies (Figure 5A). Furthermore, the majority of the colonies in the PC-3 M2 cells were larger than those in control cells (data not shown). In LNCaP cells (Figure 5A–B), the reduction in the number and dimension of the colonies directly correlated with Mitostatin expression levels.



**Figure 3. Mitostatin inhibits *in vitro* migration of prostate cancer cells.** **A and B:** Mitostatin over-expressing clones showed reduced migratory properties compared to parental cells. Migration was assessed through migration (**A**) and the wound healing assays (**B**). Cells with down-regulation of the endogenous Mitostatin protein (PC3 M2, PC3 Mitostatin shRNA, and DU145 M2) showed an increased malignant behavior. Data are expressed as percentage of migration *versus* parental cells. *Columns*, representative images of triplicates from three independent experiments; *bars*, SEM. \*  $P < 0.05$ ; \*\*  $P < 0.01$ . doi:10.1371/journal.pone.0019771.g003

*In vivo* experiments showed that xenografts derived from Mitostatin over-expressing LNCaP cells were significantly smaller than those induced by LNCaP parental cells and LNCaP V5 control cells (Figure 6A–B). Tumors derived from LNCaP B1A and LNCaP B3A reached an average volume 50% and 25% smaller than the tumors derived from parental cells. Immunohistochemical analysis of paraffin-embedded tumors and immunoblot analyses of frozen tumor xenografts (Figure 6C–D) showed high Mitostatin expression in LNCaP B1A and LNCaP B3A xenografts, compared with basal level of Mitostatin expression shown in parental cells. Mitostatin expression in transfected cells was additionally confirmed by immunohistochemical analyses using the anti-V5 tag antibody (Figure 6C).

Collectively, these findings indicate that Mitostatin is directly involved in a dose-dependent fashion in controlling one of the

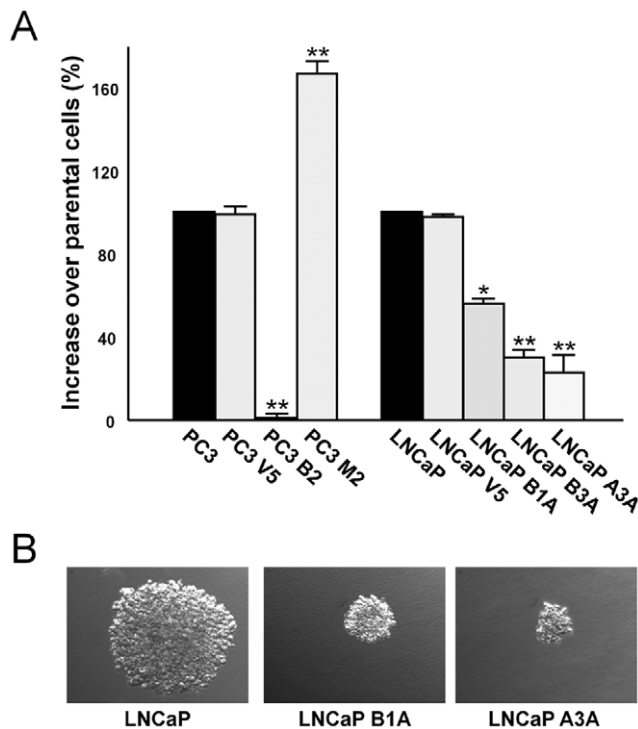


**Figure 4. Mitostatin inhibits *in vitro* invasion and adhesive properties to laminin of prostate cancer cells.** **A:** Mitostatin inhibits invasive properties of prostate cancer cells. Cells with down-regulation of the endogenous Mitostatin protein (PC3 M2, PC3 Mitostatin shRNA, and DU145 M2) showed an increased malignant behavior. **B:** Mitostatin over-expression affects cell ability to attach to laminin. Data are expressed as percentage of migration *versus* parental cells. *Columns*, representative images of triplicates from three independent experiments; *bars*, SEM. \*  $P < 0.05$ ; \*\*  $P < 0.01$ . doi:10.1371/journal.pone.0019771.g004

most powerful *in vitro* properties of malignant cells, such as anchorage independent growth, as well as *in vivo* tumorigenicity. Thus, Mitostatin is a key negative regulator of the transformed phenotype in prostate cancer.

### Mitostatin Expression is Decreased in Advanced Prostate Carcinomas

We have recently shown that Mitostatin is ubiquitously expressed in normal human tissues, but its levels are markedly attenuated in advanced stages of breast and bladder cancers [13]. To investigate Mitostatin expression in prostate cancers, we evaluated by qRT-PCR analysis 10 matched normal-cancer samples and by immunohistochemistry (IHC) three tissue microarrays composed of 293 specimens including 124 prostate cancers and 43 normal counterparts. Mitostatin mRNA levels were significantly down-regulated in the cancerous counterpart (Figure 7A;  $P = 0.029$ ). This data was further confirmed by IHC. Mitostatin was expressed mainly in the cytoplasm of the basal cell layer of the normal prostatic epithelium (Figure 7B) and a strong positivity was observed in the so called prostatic gland atrophy (Figure 7C). All the pre-



**Figure 5. Mitostatin affects anchorage-independent growth of prostate cancer cells. A:** Data from triplicate cultures of parental PC3 and LNCaP, and clones PC3 V5, PC3 B2, PC3 M2, LNCaP V5, LNCaP B1A, LNCaP B3A, and LNCaP A3A plated in soft-agar generating colonies larger than 0.2 mm in diameter. Clones over-expressing Mitostatin showed a decreased ability to form colonies, while the Mitostatin down-regulated clone, PC3 M2, showed a higher number of colonies compared to parental cells. Colonies were counted after 21 days. \*  $P < 0.05$ ; \*\*  $P < 0.01$ . **B:** Representative colonies of LNCaP parental cells (left), LNCaP B1A (middle), and LNCaP A3A (right) are shown after 21 days (magnification  $\times 200$ ). doi:10.1371/journal.pone.0019771.g005

neoplastic lesions (*i.e.*: PIN) showed a mild to moderate Mitostatin immunostaining (Figure 7D), whereas most of the adenocarcinoma showed either focal staining (Figure 7E, F) or no staining at all (Figure 7G). As expected, muscle cells and blood vessels' endothelia showed a Mitostatin moderate positivity. Of interest, five neoplastic cases had exclusively nuclear positivity. In total, 44 of the 124 tumor samples were totally negative ( $\sim 35\%$ ), 65 showed a mild to medium positivity (52.4%) and only 15 samples showed strong Mitostatin positivity (12.1%). In the univariate analysis, a decreased Mitostatin immunohistochemical score correlated with tumor stages ( $P = 0.046$ ), pT increase ( $P = 0.040$ ), and tumor volume ( $P = 0.045$ ). No clinical-pathological parameters resulted independently statistically significant associated to Mitostatin expression in the multivariate analysis. These findings further corroborate the notion that loss of Mitostatin through mutations or protein degradation could contribute to prostate cancer progression insofar as the prostate cancer specimens evaluated above derive from advanced prostate cancer patients.

## Discussion

Although prostate cancer is one of the most common malignancies, very little is known about the molecular mechanisms that determine malignant transformation of the prostatic epithelium. During prostate cancer progression, tumor cells become more motile and acquire invasive capacity. Most deaths from

prostate cancer are not due to the primary tumor but rather to secondary metastases to distant organs. For this reason it is of fundamental importance to study the mechanisms that drive prostate cancer invasion and metastases. The chromosomal region 12q has been demonstrated to be deleted in a large variety of solid advanced tumors [3–12], hence suggesting the presence, in this region, of one or more tumor suppressor genes involved in the process of cancer progression.

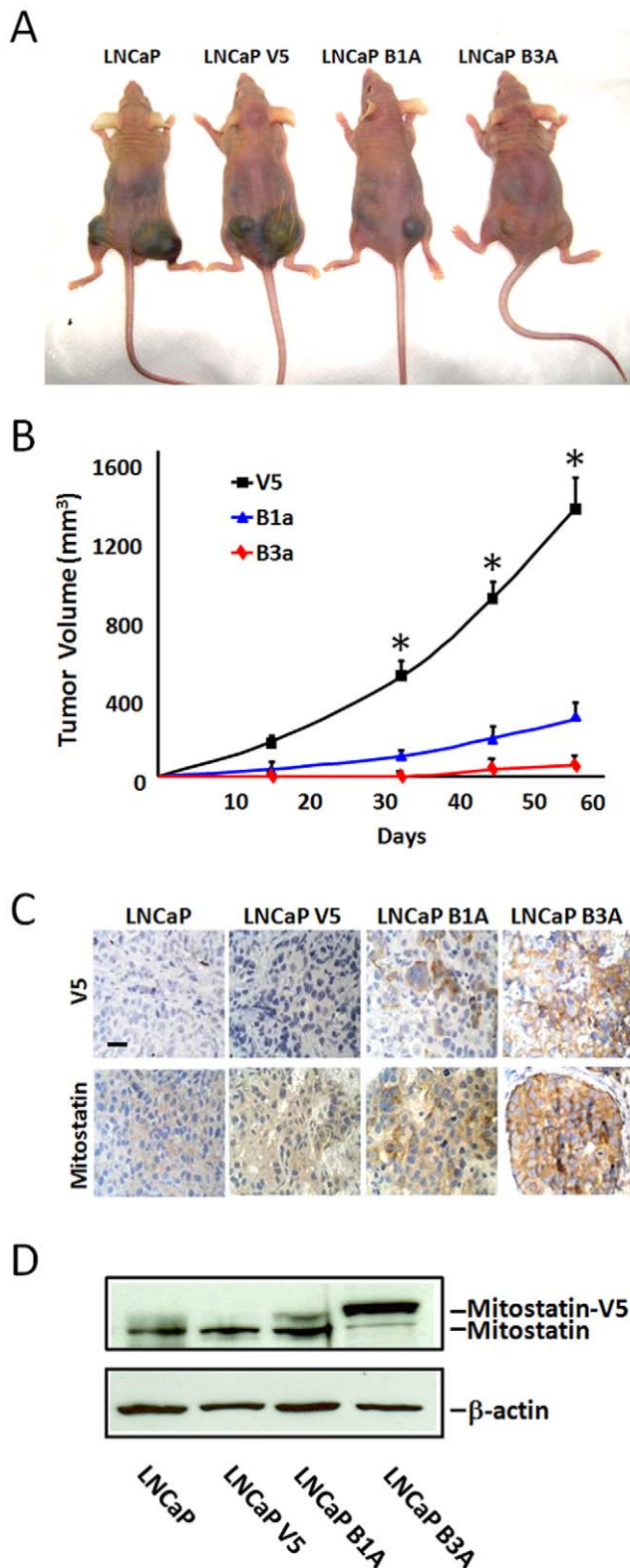
We have previously identified the Mitostatin gene, localized at 12q24.1, in the process of screening for growth-arrested genes induced by the leucine-rich proteoglycan decorin [13]. Decorin is a member of the small leucine-rich proteoglycan gene family that has recently become a focus in several areas of cancer research [20]. This soluble protein is involved in a number of cellular processes including matrix assembly, fibrillogenesis, and the control of cell proliferation [18,24–33]. Decorin has been shown to inhibit migration [16–19,34], invasion [18], and tumorigenicity [19,29,33,35,36] of a wide variety of transformed cells. Moreover, decorin induces apoptosis through the activation of caspase-3 [36,37]. Hence, it is plausible, that decorin-induced proteins could be effectors of the tumor suppressive action of this proteoglycan.

We have previously shown that Mitostatin is ubiquitously expressed in normal human tissues. However, its protein levels are markedly attenuated in advanced stages of primary mammary and urothelial neoplasms [13]. We further demonstrated that Mitostatin over-expression negatively affects cell growth and induces cell death in bladder cancer cell lines [13], suggesting that Mitostatin could behave as a classical tumor suppressor gene in other forms of malignancy. In the present study we utilized three widely used prostate carcinoma cell lines, namely, PC3 and DU145 castration-resistant cells, and LNCaP androgen-dependent cells, and utilized transgenic and immunological strategy to pinpoint the function of Mitostatin in these cells. Our results confirmed our prediction of Mitostatin belonging to the tumor suppressor gene family insofar as overexpression of Mitostatin inhibited colony formation, whereas suppression of endogenous Mitostatin caused the opposite effects.

Cell migration and invasion are fundamental components of tumor cell metastases. As increased cell migration and invasion are hallmarks of the metastatic phenotype, and thus a measure of aggressiveness, the current study provides results that implicate Mitostatin as an important protein for determining an aggressive cellular phenotype. Indeed, Mitostatin over-expressing clones showed a significant decrease in motility, and *vice-versa* by down-regulating endogenous Mitostatin with either antisense or siRNA strategies we triggered the opposite result. A direct role of Mitostatin in promoting cellular migration is also evident from our wound-healing studies, confirmed in all cell lines analyzed.

Our results demonstrate that Mitostatin regulates both cellular motility and the ability of prostate cancer cells to invade through a 3D matrix via a mechanism yet to be elucidated. Mitostatin altered the cell adhesion properties to laminin, which is the first necessary step to invade the Matrigel membrane. This finding is consistent with the role that decorin plays as a negative regulator of cell adhesion to laminin [19]. Other tumor suppressor genes have been shown to affect multiple cancer cells characteristics (migration, invasion, growth, predisposition to apoptotic stimuli) acting on important cellular protein complexes [38–40]. Thus, our future efforts will be focused on identifying Mitostatin protein's partners and on studying the possible cascade signals implicated in Mitostatin biology.

To investigate a possible direct role for Mitostatin in prostate cells transformation we performed anchorage-independent growth assays and an *in vivo* tumorigenicity in nude mice. Both studies confirmed the role of Mitostatin as a negative regulator of



**Figure 6. Effects of Mitostatin over-expression on the LNCaP cell tumorigenicity in nude mice.** **A:** Xenografts established by sub cutaneous injection of LNCaP, LNCaP V5, LNCaP B1A and LNCaP B3A cells in athymic (BALB/c *nu/nu*) were grown for 65 days. **B:** Tumor volume in animals injected with cells over-expressing Mitostatin was markedly decreased compared to tumors in animals injected with control cells. The graph illustrates the distribution in tumor sizes formed in BALB/c *nu/nu* mice through 65 days. \*:  $P < 0.05$ . **C, D:** Immunohis-

tochemical and immunoblot analysis of Mitostatin expression in LNCaP and derivative tumor xenografts. Immunohistochemistry was performed using both anti-V5 (upper panels) and anti-Mitostatin (lower panels) antibodies. Scale bar: 50  $\mu$ m. doi:10.1371/journal.pone.0019771.g006

transformation. In both experiments Mitostatin expression correlated well with the aggressiveness of cancer cells.

In this study we observed a reduction in Mitostatin expression in two prostate cancer-derived cell lines (1542CP<sub>3</sub>TX and 1532CP<sub>2</sub>TX; 16.7% of the cancer-derived cell lines) and in ~35% of a series of 124 prostate cancers. Of interest, in normal samples, the upper epithelial prostatic layer was consistently negative for Mitostatin epitopes, whereas the lower layer showed a strong positivity, suggesting the presence of a different cellular commitment in Mitostatin expression. A strong positivity was always observed in the so called prostatic gland atrophy (a common process typically but not exclusively found in older patients), while a moderate positivity was observed in all the pre-neoplastic lesions, with a decrease in the most advanced prostate cancer stages. In primary prostate tumors, Mitostatin down-regulation was statistically associated with advanced tumor stages and increased size (or direct extent) of the primary tumor at pathological examination (*i.e.*: pT), confirming our previous observation in breast and bladder cancer [13]. These results suggest that down-regulation of Mitostatin during the later stages of prostate tumorigenesis could promote cancer progression. We did not find any correlation between Mitostatin expression and other clinical parameters used to assess prostate cancer poor prognosis, such as Gleason grade, though this point remains to be investigated in a larger series of cases.

In conclusion, the present study provides the first evidence that Mitostatin might play a significant role as tumor suppressor in prostate tumor development and progression through its inhibitory effects on cell migration, invasion, anchorage-independent growth, and *in vivo* tumorigenesis. Moreover, Mitostatin level is decreased in advanced stages of primary prostate cancers. Taken together, these data further support the hypothesis that Mitostatin acts as a *bona fide* tumor suppressor and suggest that further investigations of Mitostatin as a useful clinical marker for diagnosis and prognosis in prostate tumors are warranted.

## Materials and Methods

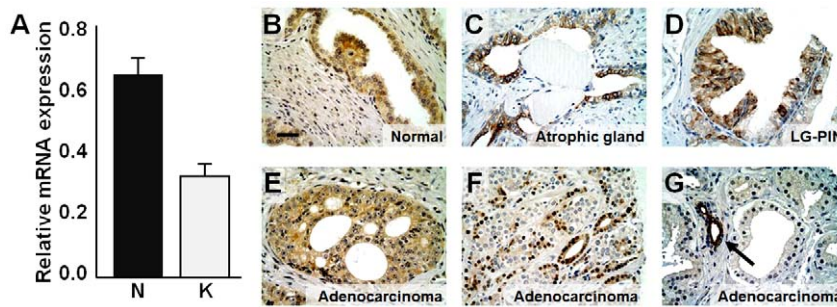
### Cell Culture and Generation of Stable Clones

Prostate cancer derived cell lines 2220, 2221, 11609, 11610, 11611, TSUP, 1532CP<sub>2</sub>TX, 1535CP<sub>1</sub>TX, 1542CP<sub>3</sub>TX, LNCaP, DU145, and PC3 and prostate immortalized normal derived cell lines 1535NPTX, and 1542NPTX were obtained from American Type Culture Collection (ATCC, Manassas, VA) and maintained as recommended. Cells were transfected as previously described [13,41] (Data S1), and selected in medium supplemented with either G418 (400  $\mu$ g/ml) or puromycin (0.75  $\mu$ g/ml) for 3 weeks.

### Mitostatin Gene Silencing

Gene silencing of human Mitostatin was achieved by siRNA strategies using validated SureSilencing Mitostatin siRNA and control plasmids (SuperArray Bioscience Corp, Frederick, MD). PC3 cells were transfected with vehicle (DEPC-treated water), control siRNA (scrambled), or siRNA directed against Mitostatin (100 pmol/L) using Oligofectamine<sup>TM</sup> reagent (Invitrogen, Carlsbad, CA) following manufacturer's protocols. Twenty-four hours after transfection, PC3 cells were starved in serum-free medium (SFM) for 12 hours and then were processed and analyzed for





**Figure 7. Mitostatin is down-regulated in human prostate cancers.** **A:** Relative fold of Mitostatin mRNA levels in normal prostatic tissue samples (N, black), and Gleason 7 prostate cancer samples (K, bright gray). Mitostatin showed a consistent down-regulation in cancer tissues ( $P=0.029$ ). Columns, representative images of triplicates; bars, SD. **B–G:** Immunohistochemical detection of Mitostatin in human prostate. Mitostatin protein is localized in the cytoplasm of normal (B) and atrophic (C) prostatic glands. Higher levels of Mitostatin protein were observed in PIN lesions (D) and in some tumors (E). **F:** In addition to a weak staining, Mitostatin was also detected in the nuclei in few cases of adenocarcinoma. **G:** Mitostatin expression is present in an atrophic gland (black arrow) in contrast with the surrounding negative neoplastic glands. Scale bar: 50  $\mu$ m. doi:10.1371/journal.pone.0019771.g007

migration and invasion as described below. The expression of Mitostatin protein was detected by immunoblot analysis (Figure S1).

### Colony Formation and Migration Assays

Cells were plated at a density of 400 cells/100 mm dish. On day 15, cells were fixed in 10% formalin [100% formaldehyde is 37%, thus 3.7% is 10% formalin, *i.e.*: PBS-formaldehyde] and stained with crystal violet for colony counting [21]. Cells were serum starved for 24 hours. Cells ( $2.5 \times 10^4$  in 200  $\mu$ l) were then seeded in Boyden chambers (upper chamber) (BD Biocoat, Bedford, MA). Lower chambers contained 500  $\mu$ l of either SFM or 1% or 5% serum. After 10 hours, migrated cells were counted under the microscope after fixing and staining in Coomassie blue as described [42,43].

### Migration, Invasion and Adhesion Assays

Cells were seeded onto 35-mm plates in serum-containing medium until sub-confluence and then transferred to SFM. After 24 hours, the plates were scratched with a thin disposable tip to generate a wound in the cell monolayer [42]. Cells were incubated for additional 72 hours in 1% or 5% serum-containing medium and analyzed and photographed with a Zeiss Axiovert 200 M cell live microscope (Carl Zeiss Inc., Thornwood, NY) using the Metamorph Image Acquisition and Analysis software (Universal Imaging, Downingtown, PA) at the Kimmel Cancer Center Confocal Microscopy Core Facility. Cell invasion through a three-dimensional extracellular matrix was assessed by a Matrigel invasion assay using BD Matrigel Invasion Chambers (BD Biocoat) with 8.0- $\mu$ m filter membranes as previously described [42,43]. For adhesion assays, 96-well plates, coated with mouse laminin (BD Biocoat), were incubated at room temperature for 1 hour with 1% bovine serum albumin (BSA) (Sigma, St. Louis, MO), to block unspecific binding. 100,000 cells/well were seeded in triplicates and allowed to adhere for 2 hours at 37°C and non-adherent cells were then removed with two washes. Adherent cells were stained with CyQUANT NF Cell Proliferation Assay kit (Invitrogen) and the absorbance was read at 490 nm. Background levels of cell adhesion in wells coated with BSA alone were subtracted from values obtained for laminin.

### Anchorage-independent Growth and Tumorigenicity Assays

For soft agar assay, cells were suspended in 0.2% agarose in DMEM 10% FBS medium, plated at a density of  $10^3$  cells in a 60-

mm dish coated previously with 0.4% agarose, and maintained at 37°C. On day 21, colonies >0.2 mm in diameter were counted and analyzed [21]. Tumorigenicity assays were carried out essentially as described [44], under protocols approved by the Thomas Jefferson Animal Care and Use Committee. Immunodeficient, athymic nude (BALB/c *nu/nu*) mice were injected subcutaneously into posterior flanks with  $2 \times 10^6$  cells in 200  $\mu$ l of Matrigel basement membrane matrix (BD Biosciences). Tumor growth was monitored daily for 65 days.

### Ethic statements

All patients involved in the qRT-PCR study gave their written informed consent. All human samples used in the immunohistochemical study were purchased from Pentagen Inc. (Seoul, Korea), which has the require permissions and patients' consents. The University of Padova and the Thomas Jefferson University institutes' ethical regulations on research conducted on human tissues were followed.

### Reverse Transcription and Quantitative Real Time PCR

A total of 10 cases of Gleason 7 (3+4) prostate cancers were retrieved from the archives of the Surgical Pathology & Cytopathology Unit of the University of Padova. In each case, two 2-mm tissue cores were obtained from the macrodissected paraffin blocks from the tumor and from the adjacent non-cancerous prostatic tissue. The tissue cores were deparaffinised with xylene at 50°C for 3 min. Total RNA was extracted using the RecoverAll kit (Ambion, Austin, Texas, USA). Reverse Transcription was performed using 100 ng of total RNA, M-MLV Reverse Transcriptase (Invitrogen) and 250  $\mu$ M random primers (Invitrogen). Quantitative Real Time PCR analyses were performed with the LightCycler 480 Real-Time PCR System (Roche Diagnostics, Mannheim, Germany). Experiments were performed according to a standard protocol using the LightCycler 480 Probes Master (Roche). B2M was included as housekeeping gene control to correct for equal RNA amounts. Primer sequences and respective probes were designed using the Universal ProbeLibrary (Roche) and the ProbeFinder software (<http://www.roche-applied-science.com/>): Mitostatin forward 5'-GGG GGA CTC TTC GGA AAC-3', Mitostatin reverse 5'TGT CGT GCT AGC TGC TGA TT-3'; B2M forward 5'-CCT TGA GGC TAT CCA GCG TA-3', B2M reverse 5'-TCA GGA AAT TTG ACT TTC CAT TC-3'. All the reactions were run in triplicate, including no-template controls.

## Immunoblotting and Immunohistochemical Analyses

Protein extraction and immunoblot analyses were performed as described previously [13,21,43] (Data S1). Anti-Mitostatin [13] 1:1,000 and anti- $\beta$ -actin 1:10,000 (Sigma) were used as primary antibodies. Immunohistochemistry was performed as previously described [13,21] (Data S1). Sections were immunostained overnight at room temperature with a 1:100 dilution of the anti-Mitostatin antibody or pre-immune serum as control. AccuMax Array (Petagen Inc.) A222, A223 and A302 including 293 0.6-mm cores were utilized for the immunohistochemical study. Samples contained on the Array were derived from Korean patients and clinical pathological information was also provided. All sections were examined independently by two investigators (R.B., M.G.), and complete agreement was reached for Mitostatin positivity and negativity. Regarding the morphology and the intensity of Mitostatin expression, positive staining of anti-Mitostatin antibody was semiquantified with a three-tier system (0 = negative; 1+ = mild to moderate immunoreactions; 2+ = strong immunoreactions).

## Statistical Analysis

Statistical analysis was carried out with SigmaStat for Windows version 3.10 (Systat Software Inc., Point Richmond, CA). All values were expressed as mean  $\pm$  SE or SD. Differences between means were evaluated with double-sided  $Z$ -test. The  $\chi^2$  test was used to examine the categorical variables and the association between Mitostatin immunohistochemical expression levels and other clinico-pathological variables in univariate analysis. To identify variables independently associated to Mitostatin immu-

nohistochemical levels, backward selection multivariate analysis was performed using the logistic regression model. Differences were considered statistically significant at  $P < 0.05$ .

## Supporting Information

**Figure S1 Depletion of endogenous Mitostatin in PC3 cells.** Gene knockout for MITOSTATIN was achieved by siRNA. Twenty-four hours after transfection, PC3 cells were serum starved for 24 hours and processed and analyzed for migration and invasion. The expression of Mitostatin protein was detected by immunoblot using anti-Mitostatin antibody. Protein loading was normalized using anti- $\beta$ -actin polyclonal antibodies.

(TIF)

**Data S1**

(DOC)

## Acknowledgments

We thank James LeNoir and Rhonda Walters for their technical assistance and Dr. L. Sorzano for his help and expert advice in the initial stages of this work.

## Author Contributions

Conceived and designed the experiments: MF AM RVI RB. Performed the experiments: MF DD JL AV BW. Analyzed the data: MF DS-B LGG AM RVI RB. Contributed reagents/materials/analysis tools: MPG PM MR LGG AM RB. Wrote the paper: MF AM RB.

## References

- Jemal A, Siegel R, Xu J, Ward E (2010) Cancer statistics, 2010. *CA Cancer J Clin* 59: 225–249.
- Vecchione A, Gottardo F, Gomella LG, Wildemore B, Fassan M, et al. (2007) Molecular genetics of prostate cancer: clinical translational opportunities. *J Exp Clin Cancer Res* 26: 25–37.
- Field JK, Kiaris H, Risk JM, Tsiriyotis C, Adamson R, et al. (1995) Allelotype of squamous cell carcinoma of the head and neck: fractional allele loss correlates with survival. *Br J Cancer* 72: 1180–1188.
- Shiseki M, Kohno T, Adachi J, Okazaki T, Otsuka T, et al. (1996) Comparative allelotype of early and advanced stage non-small cell lung carcinomas. *Genes Chromosomes Cancer* 17: 71–77.
- Tirkkonen M, Johannsson O, Agnarsson BA, Olsson H, Ingvarsson S, et al. (1997) Distinct somatic genetic changes associated with tumor progression in carriers of BRCA1 and BRCA2 germ-line mutations. *Cancer Res* 57: 1222–1227.
- Schmutte C, Baffa R, Veronese LM, Murakumo Y, Fishel R (1997) Human thymine-DNA glycosylase maps at chromosome 12q22-q24.1: a region of high loss of heterozygosity in gastric cancer. *Cancer Res* 57: 3010–3015.
- Kimura M, Furukawa T, Abe T, Yatsuoka T, Youssef EM, et al. (1998) Identification of two common regions of allelic loss in chromosome arm 12q in human pancreatic cancer. *Cancer Res* 58: 2456–2460.
- Jiang F, Richter J, Schraml P, Bubendorf L, Gasser T, et al. (1998) Chromosomal imbalances in papillary renal cell carcinoma: genetic differences between histological subtypes. *Am J Pathol* 153: 1467–1473.
- Koo SH, Kwon KC, Ihm CH, Jeon YM, Park JW, et al. (1999) Detection of genetic alterations in bladder tumors by comparative genomic hybridization and cytogenetic analysis. *Cancer Genet Cytogenet* 110: 87–93.
- Rijken AM, Hu J, Perlman EJ, Morsberger LA, Long P, et al. (1999) Genomic alterations in distal bile duct carcinoma by comparative genomic hybridization and karyotype analysis. *Genes Chromosomes Cancer* 26: 185–191.
- Aubele MM, Cummings MC, Mattis AE, Zitzelsberger HF, Walch AK, et al. (2000) Accumulation of chromosomal imbalances from intraductal proliferative lesions to adjacent in situ and invasive ductal breast cancer. *Diagn Mol Pathol* 9: 14–19.
- Sattler HP, Rohde V, Bonkhoff H, Zwergel T, Wullich B (1999) Comparative genomic hybridization reveals DNA copy number gains to frequently occur in human prostate cancer. *Prostate* 39: 79–86.
- Vecchione A, Fassan M, Anesti V, Morrione A, Goldoni S, et al. (2009) MITOSTATIN, a putative tumor suppressor on chromosome 12q24.1, is downregulated in human bladder and breast cancer. *Oncogene* 28: 257–269.
- Kim YR, Kim SS, Yoo NJ, Lee SH (2010) Mutational Analysis of MITOSTATIN, a candidate tumor-suppressor gene, at a mononucleotide repeat in gastric and colorectal carcinoma. *Gut and Liver* 4: 149–150.
- Cerqua C, Anesti V, Pyakurel A, Liu D, Naon D, et al. (2010) Trichoplein/Mitostatin regulates endoplasmic reticulum-mitochondria juxtaposition. *EMBO Rep* 11: 854–860.
- Merle B, Durussel L, Delmas PD, Clezardin P (1999) Decorin inhibits cell migration through a process requiring its glycosaminoglycan side chain. *J Cell Biochem* 75: 538–546.
- Kinsella MG, Fischer JW, Mason DP, Wight TN (2000) Retrovirally mediated expression of decorin by macrovascular endothelial cells. Effects on cellular migration and fibronectin fibrillogenesis in vitro. *J Biol Chem* 275: 13924–13932.
- Xu G, Guimond MJ, Chakraborty C, Lala PK (2002) Control of proliferation, migration, and invasiveness of human extravillous trophoblast by decorin, a decidua product. *Biol Reprod* 67: 681–689.
- Grant DS, Yenisey C, Rose RW, Tootell M, Santra M, et al. (2002) Decorin suppresses tumor cell-mediated angiogenesis. *Oncogene* 21: 4765–4777.
- Parcellier A, Schmitt E, Gurbuxani S, Seigneurin-Berny D, Pance A, et al. (2003) HSP27 is a ubiquitin-binding protein involved in I-kappaBalpha proteasomal degradation. *Mol Cell Biol* 23: 5790–5802.
- Monami G, Emiliozzi V, Bitto A, Lovat F, Xu SQ, et al. (2009) Proepithelin regulates prostate cancer cell biology by promoting cell growth, migration, and anchorage-independent growth. *Am J Pathol* 174: 1037–1047.
- Rabinovitz I, Cress AE, Nagle RB (1994) Biosynthesis and secretion of laminin and S-laminin by human prostate carcinoma cell lines. *Prostate* 25: 97–107.
- Edlund M, Miyamoto T, Sikes RA, Ogle R, Laurie GW, et al. (2001) Integrin expression and usage by prostate cancer cell lines on laminin substrata. *Cell Growth Differ* 12: 99–107.
- Goldoni S, Iozzo RV (2008) Tumor microenvironment: Modulation by decorin and related molecules harboring leucine-rich tandem motifs. *Int J Cancer* 123: 2473–2479.
- Danielson KG, Fazzio A, Cohen I, Cannizzaro LA, Eichstetter I, et al. (1993) The human decorin gene: intron-exon organization, discovery of two alternatively spliced exons in the 5' untranslated region, and mapping of the gene to chromosome 12q23. *Genomics* 15: 146–160.
- Santra M, Skorski T, Calabretta B, Lattime EC, Iozzo RV (1995) De novo decorin gene expression suppresses the malignant phenotype in human colon cancer cells. *Proc Natl Acad Sci U S A* 92: 7016–7020.
- Santra M, Mann DM, Mercer EW, Skorski T, Calabretta B, et al. (1997) Ectopic expression of decorin protein core causes a generalized growth suppression in

- neoplastic cells of various histogenetic origin and requires endogenous p21, an inhibitor of cyclin-dependent kinases. *J Clin Invest* 100: 149–157.
28. Moscatello DK, Santra M, Mann DM, McQuillan DJ, Wong AJ, et al. (1998) Decorin suppresses tumor cell growth by activating the epidermal growth factor receptor. *J Clin Invest* 101: 406–412.
  29. Csordas G, Santra M, Reed CC, Eichstetter I, McQuillan DJ, et al. (2000) Sustained down-regulation of the epidermal growth factor receptor by decorin. A mechanism for controlling tumor growth in vivo. *J Biol Chem* 275: 32879–32887.
  30. Schonherr E, Levkau B, Schaefer L, Kresse H, Walsh K (2001) Decorin-mediated signal transduction in endothelial cells. Involvement of Akt/protein kinase B in up-regulation of p21(WAF1/CIP1) but not p27(KIP1). *J Biol Chem* 276: 40687–40692.
  31. Xaus J, Comalada M, Cardo M, Valledor AF, Celada A (2001) Decorin inhibits macrophage colony-stimulating factor proliferation of macrophages and enhances cell survival through induction of p27(Kip1) and p21(Waf1). *Blood* 98: 2124–2133.
  32. Goldoni S, Iozzo RA, Kay P, Campbell S, McQuillan A, et al. (2007) A soluble ectodomain of LRIG1 inhibits cancer cell growth by attenuating basal and ligand-dependent EGFR activity. *Oncogene* 26: 368–381.
  33. Goldoni S, Seidler DG, Heath J, Fassan M, Baffa R, et al. (2008) An antimetastatic role for decorin in breast cancer. *Am J Pathol* 173: 844–855.
  34. Ferdous Z, Peterson SB, Tseng H, Anderson DK, Iozzo RV, et al. (2010) A role for decorin in controlling proliferation, adhesion, and migration of murine embryonic fibroblasts. *J Biomed Mater Res A* 93: 419–428.
  35. Reed CC, Gauldie J, Iozzo RV (2002) Suppression of tumorigenicity by adenovirus-mediated gene transfer of decorin. *Oncogene* 21: 3688–3695.
  36. Seidler DG, Goldoni S, Agnew C, Cardi C, Thakur ML, et al. (2006) Decorin protein core inhibits in vivo cancer growth and metabolism by hindering epidermal growth factor receptor function and triggering apoptosis via caspase-3 activation. *J Biol Chem* 281: 26408–26418.
  37. Tralhao JG, Schaefer L, Micegova M, Evaristo C, Schonherr E, et al. (2003) In vivo selective and distant killing of cancer cells using adenovirus-mediated decorin gene transfer. *Faseb J* 17: 464–466.
  38. Tamura M, Gu J, Matsumoto K, Aota S, Parsons R, et al. (1998) Inhibition of cell migration, spreading, and focal adhesions by tumor suppressor PTEN. *Science* 280: 1614–1617.
  39. Tamura M, Gu J, Takino T, Yamada KM (1999) Tumor suppressor PTEN inhibition of cell invasion, migration, and growth: differential involvement of focal adhesion kinase and p130Cas. *Cancer Res* 59: 442–449.
  40. Shi HY, Zhang W, Liang R, Abraham S, Kittrell FS, et al. (2001) Blocking tumor growth, invasion, and metastasis by maspin in a syngeneic breast cancer model. *Cancer Res* 61: 6945–6951.
  41. Romano G, Reiss K, Tu X, Peruzzi F, Belletti B, et al. (2001) Efficient in vitro and in vivo gene regulation of a retrovirally delivered pro-apoptotic factor under the control of the *Drosophila* HSP70 promoter. *Gene Ther* 8: 600–607.
  42. Monami G, Gonzalez EM, Hellman M, Gomella LG, Baffa R, et al. (2006) Proepithelin promotes migration and invasion of 5637 bladder cancer cells through the activation of ERK1/2 and the formation of a paxillin/FAK/ERK complex. *Cancer Res* 66: 7103–7110.
  43. Lovat F, Bitto A, Xu SQ, Fassan M, Goldoni S, et al. (2009) Proepithelin is an autocrine growth factor for bladder cancer. *Carcinogenesis* 30: 861–868.
  44. Vecchione A, Ishii H, Baldassarre G, Bassi P, Trapasso F, et al. (2002) FEZ1/LZTS1 is down-regulated in high-grade bladder cancer, and its restoration suppresses tumorigenicity in transitional cell carcinoma cells. *Am J Pathol* 160: 1345–1352.