Inhibition of Tumor Growth and Metastasis by a Combination of Anti-VEGF-C and Enhanced IL-12 Therapy in an Immunocompetent Mouse Mammary Cancer Model

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1. Introduction

Breast cancer represents a major health problem in women, with more than 1,000,000 new cases and 370,000 deaths yearly worldwide [1]. Perhaps more worrisome is an apparently increasing incidence of breast cancer among younger women under 40 years of age recently reported in many countries worldwide [2-4]. The lethality of breast cancer is largely due to metastasis, preferentially to the lymph nodes, lungs and bones [5]; in order to delay the progression of breast cancer and prolong patient life, more effective chemopreventive and antimetastatic treatments and less toxic chemotherapeutic agents are desperately required.

Vascular endothelial growth factor-C (VEGF-C) is expressed in a variety of malignant tumors including mammary cancer [6] and over-expression of VEGF-C has been reported to be associated with lymph node metastasis and poor prognosis in breast cancer patients [7,8]. A number of animal studies using cell lines [9-11] and transgenic mice[12] have been conducted in an attempt to demonstrate that VEGF-C over-expression is able to promote cancer metastasis. Using a 'RNA interference' approach with an immunocompetent mouse mammary cancer model, we previously demonstrated that inhibition of VEGF-C or VEGF-A by gene silencing using vectors expressing short interfering RNA (siRNA) leads to suppression of lymphatic and/or hematogenous metastasis [13].

The cytokine interleukin-12 (IL-12), a heterodimer composed of p35 and p40 subunits, is produced primarily by dendritic cells, macrophages/monocytes, and neutrophils and functions in enhancing the activity of cytotoxic T lymphocytes and NK cells. Both subunits are necessary to exert biological activity [14]. IL-12 plays an important role in the induction of a cell-mediated immune response [15]. This cytokine is also involved in the differentiation of native T cells to the Th1 subset, and induces production of interferon-γ (IFNγ) in both T and NK cells. In addition, IL-12 has been shown to exert a potent anti-neoplastic effect in a variety of tumors in animal models [16-19]. The anti-tumor activity of IL-12 is considered to be due to anti-angiogenic effects as well as to induction of immune response [19-21]. The number of $CD8^+$ T cells and dendritic cells is significantly elevated in induced murine mammary tumors stably transfected with VEGF-C siRNA, suggesting that VEGF-C modulates the immune response [22]. Based on the above evidence, we chose to use an immunocompetent mammary cancer model in this study.

2. Materials and methods

2.1 BJMC3879 cell line

Mouse mammary tumor virus (MMTV), isolated and purified from medium in which Jyg-MC cells (established from mammary tumors of the Chinese wild mouse) were grown, was inoculated into the inguinal mammary glands of female BALB/c mice, resulting in the development of mammary carcinomas [23]. The BJMC3879 mammary adenocarcinoma cell line was subsequently derived from a metastatic focus within a lymph node from one of the inoculated mice and the cell line continues to show a high metastatic propensity, especially to lymph nodes and lungs [19,24,25]. We maintain the BJMC3879 cell line in either RPMI-1640 medium or Dulbecco's Modified Eagle's medium containing 10% fetal bovine serum supplemented with streptomycin/penicillin in an incubator at 37°C under a 5% CO_2 atmosphere.

2.2 Animals

Forty female 6-week-old BALB/c mice were used in this study (Japan SLC, Inc., Hamamatsu, Japan). The animals were housed no more than 5 per plastic cage on wood chip bedding with free access to water and food and maintained under conditions of controlled temperature (21 ± 2 °C), humidity (50 ± 10 %), and lighting (12 h-12 h light-dark cycle). All animals were held for a 1-week acclimatization period before study commencement. This animal experiment was approved by the Animal Experiment Committee of Osaka Medical College. Husbandry was in accordance with the procedures outlined in the Guide for the Care and Use of Laboratory Animals at Osaka Medical College, the Japanese Government Animal Protection and Management Law (No.105) and the Japanese Government Notification on Feeding and Safekeeping of Animals (No.6).

2.3 Vectors for VEGF-C siRNA and IL-12 expression

We used short hairpin RNAs (shRNA) targeting mouse VEGF-C to generate siRNA. The previously determined mouse VEGF-C siRNA sequence, 5′-GCATGAACACCAGCACAGGTT*ccaagag*AACCTGTGCTGGTGTTCATGC-3′, [13] contains a 21-nucleotide sequence in sense and antisense orientation separated by a 7-nucleotide spacer (indicated above by small letters in italics). The complementary oligonucleotide was annealed and ligated into a *Bbs*I/*Bbs*I-digested psiRNA-h7SKGFP-zeo vector (InvivoGen, Inc., San Diego, CA, USA). This vector contains the human 7SK promoter (an RNA polymerase III promoter), which can generate high amounts of shRNAs [26]. We identified positive clones by restriction digestion and confirmed by sequencing.

The plasmid, pORF-mIL-12 (InvivoGen, Inc., San Diego, CA, USA), encodes for the mouse IL-12 gene; it is an active fusion of the p35 and p40 subunits linked by bovine elastin motifs to express IL-12 as a single peptide with the signal sequence in the p35 subunit. This vector is regulated by the elongation factor –1α (EF-1α)/human T cell leukemia virus type 1 (HTLV-1) long terminal repeat hybrid promoter and has previously shown anti-neoplastic effects [19]. To produce the empty control vector, we deleted the *IL-12* gene from pORF-mIL-12 via digestion with *NcoI/NheI*.

2.4 *In vivo* gene therapy using VEGF-C siRNA and/or IL12 expression vectors

BJMC3879 cells (5 x 10^6 cells/0.3 ml in phosphate buffered saline) were inoculated into the right inguinal region of the 40 female BALB/c mice and the animals randomly allocated into 4 groups - pVec (control), psiVEGF-C, pIL12, and psiVEGF-C+pIL12 - of 10 mice each. Two weeks post-inoculation, when the tumors had reached 0.2–0.4 cm in diameter, we injected either psiVEGF-C, pIL12 or psiRNA-VEGF-C+pIL12, or the pVec control directly into the tumors of mice in the appropriate treatment groups. The vectors were injected using a 27-guage needle at a concentration of 0.5µg/µl in sterile saline while the animals were under isoflurane anesthesia. A total volume of 150 µl was introduced into larger tumors (more than 0.6 cm in maximum diameter), while smaller tumors of 0.6 cm in maximum diameter were infused until we detected leakage of the vector solution. Immediately after vector injection, we performed *in vivo* gene electrotransfer by applying a conductive gel (Echo Jelly; Aloka., Co., Ltd., Tokyo, Japan) topically to the unshaved skin over the injected tumor. Electric pulses were delivered directly to the tumor via "forceps" platinum plate electrodes (CUY650-10; Nepa Gene Co., Ltd., Ichikawa, Japan) using a CUY21EDIT square-wave electropulser (Nepa Gene Co., Ltd.). We had previously determined the parameters for optimal gene electrotransfer: for intratumoral injection of 50-75 µg plasmid (dependent on tumor size as mentioned above), 8 pulses with a pulse length of 20 milliseconds at 100 volts proved to be most efficient [13,24,27].

Using calipers, we measured the size of each treated mammary tumor weekly and calculated tumor volumes using the formula *maximum diameter x (minimum diameter)*^{2} *x 0.4* [28]. Individual body weights were also recorded at weekly intervals. All surviving animals received 50 mg/kg 5-bromo-2'-deoxyuridine (BrdU; Sigma Co., St. Lois, MO, USA) i.p. at 1 h prior to sacrifice.

2.5 Histopathological analysis

After 8 weeks of treatment and observation/ tumor measurement, all mice were euthanized under isoflurane anesthesia and the mammary tumors and certain lymph nodes (specifically, nodes from axillary and femoral regions, as well as any that appeared abnormal) were removed. We then immediately fixed a portion of each tissue sample in 10% phosphate-buffered formalin. Lungs were routinely inflated with the fixative, excised, and immersed back into the phosphate-buffered formalin. We subsequently trimmed and examined all lobes for metastatic foci before processing all tissues through to paraffin blocks, after which they were cut into 4-µm-thick sections and stained with hematoxylin and eosin (H&E) for histopathological examination or left unstained for immunohistochemistry.

2.6 Immunohistochemical analysis of mammary tumors for microvascular density and dilated lymphatic vessels

To quantitatively assess blood and lymphatic microvessel density in the primary mammary carcinomas, we used the avidin-biotin immunohistochemical complex method (LSAB kit;

DakoCytomation) with a rabbit polyclonal antibody against CD31 (Lab Vision Co., CA, USA), a specific marker for blood vessel endothelium, and a hamster anti-podoplanin monoclonal antibody (AngioBio Co., Del Mar, CA, USA) targeted to lymphatic endothelium. The number of CD31-positive blood microvessels was counted as previously described [29]; briefly, we scanned slides at low-power (X100) magnification to identify those areas having the highest number of vessels and the 5 areas of highest microvascular density were then selected and counted at higher (X200–400) magnification to obtain mean ± SD values. We counted the number of podoplanin-positive lymphatic vessels containing intralumenal tumor cells and expressed the numbers of immunopositive structures as an average ± SD.

2.7 Statistical analyses

We analyzed significant differences in the quantitative data between groups using the Student's *t*-test via the method of Welch, which provides for insufficient homogeneity of variance. The differences in metastatic incidence we examined by Fisher’s exact probability test, with $P<0.05$ or $P<0.01$ considered to represent a statistically significant difference.

3. Results

3.1 Body weights and tumor growth

No mortality was observed in this study. At experimental weeks 2 through 6, body weights in mice receiving pIL12 and the combination psiVEGF-C + pIL12 treatment began to decrease compared to both control and psiVEGF-C alone. Though mild (less than 5% reduction compared to the controls), weight loss was consistently significant in the combination group during this 4-week period, but the pIL12 group showed statistically lower weights intermittently at weeks 2 and 4 (Fig. 1A). The general condition of the animals was good throughout the experiment. At conclusion of the study at week 8, body weights were roughly equivalent across treatment groups; however, as can be seen in Figure 1B, the tumor volumes of all 3 treatment groups were significantly suppressed from experimental weeks 3 to termination as compared to the pVec controls. The average tumor volumes at week 8 were as follows: pVec control group, 1715 ± 662 mm^3; psiVEGF-C group, 954 ± 470 mm^3; pIL12 group, 756 ± 343 mm^3; psiVEGF-C + pIL12 group, 860 ± 437 mm^3.

3.2 Tumor morphology and metastases

Histopathologically, all mammary carcinomas proved to be moderately differentiated adenocarcinomas. Representative histologic morphologies of lymph node and lung metastases are illustrated in Figures 2A-H. Both the metastatic incidence and multiplicity in lymph node and lung was markedly reduced in all treatment groups as compared to control; as illustrated in Figures 3A and B for lymph node metastasis and Figures 3C and D for lung metastasis, the reductions were statistically significant within the parameters of overall node and lung metastatic incidence and in the number of larger metastatic lung foci >250 μm. Treatment with pIL12 alone appears to be more effective in inhibiting tumor spread than psiVEGF-C, but by all criteria evaluated, the psiVEGF-C + pIL12 combination yielded the greatest reductions in metastatic spread and severity over either psiVEGF-C alone, pIL12 alone, or pVec control (Figures.3B and D).

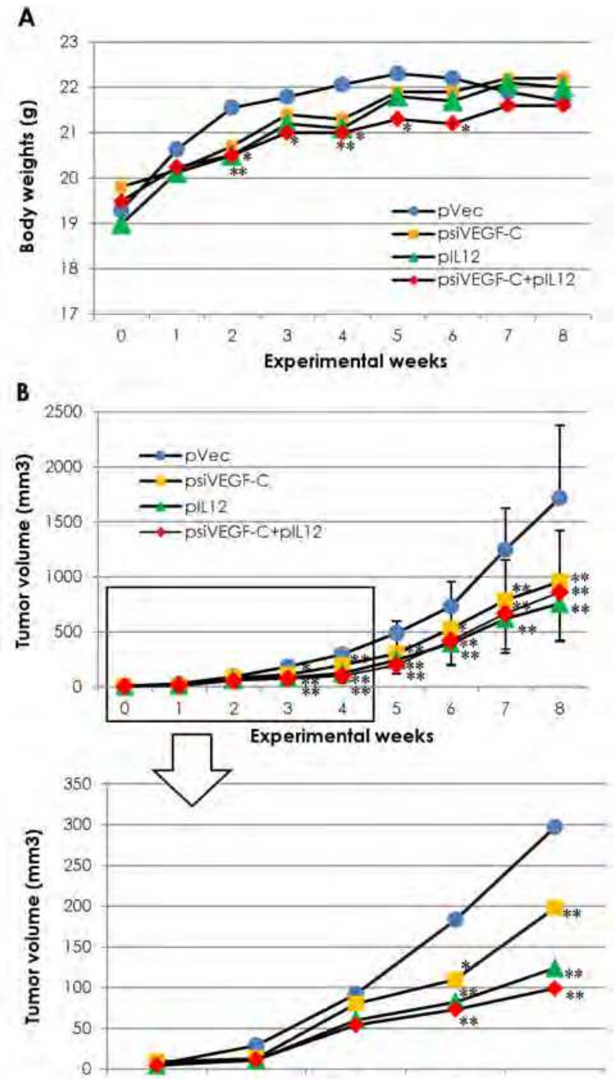

Fig. 1. Body weights (**A**) and mammary tumor volumes (**B**) in female BALB/c mice treated with pVec (control), psiVEGF-C, pIL12, and the psiVEGF-C+pIL12 combination vector. (**A**) Body weights were significantly lower in the pIL12 group at weeks 2 and 4, and in the psiVEGF-C+pIL12 combination group from weeks 2 through 6, as compared to the pVec group. (**B**) Increases in tumor volume were significantly suppressed in mice transfected with either psiVEGF-C alone, pIL12 alone, or combined psiVEGF-C+pIL12 at weeks 3 – 8 (experiment termination) compared to pVec -treated control mice. The data for body weights at weeks 0 – 4 are magnified. Data represent mean ± SD. **P*<0.05; ***P*<0.01 compared with pVec controls.

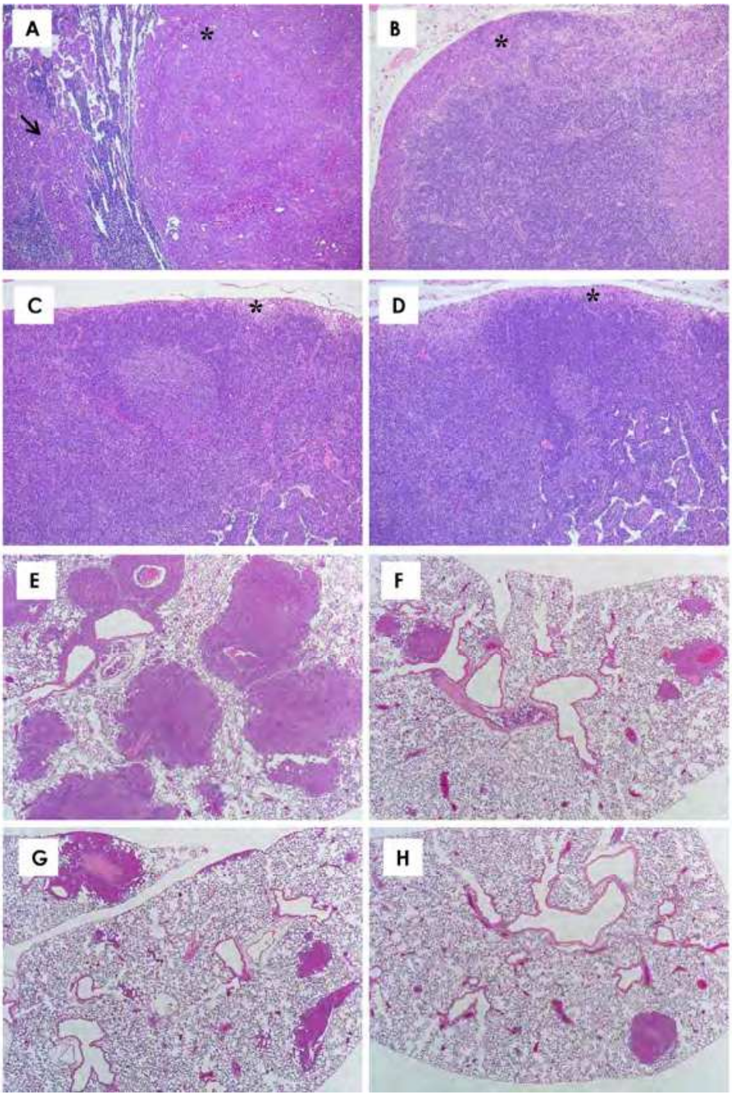

Fig. 2. Metastasis to a lymph node (**A-D**). (**A**) Metastatic carcinoma cells fill the sinusoidal space (arrow) in a control mouse. (**B**) A lymph node from a tumor injected with psiVEGF-C. Metastatic carcinoma cells filled the subcapsular sinus (asterisk). (**C**) and (**D**) No metastatic cells are observed in the subcaspsular sinus of a lymph node from a mouse in the pIL12 group (**C**), or from an animal in the combination psiVEGF-C+pIL12 group (**D**), but histiocytes are acummulating here in each case (asterisks). (**E**) Metastatic foci in the lung of a control (pVec) mouse. Many metastatic foci and small to large nodules were seen. (**F-H**) Metastatic foci tended to be smaller in mice receiving psiVEGF-C (**F**), pIL12 (**G**), and the combination vector (**H**) than those observed in the pVec group (**E**). H&E staining. Magnification: **A-D**, x100; **E-H**, x40.

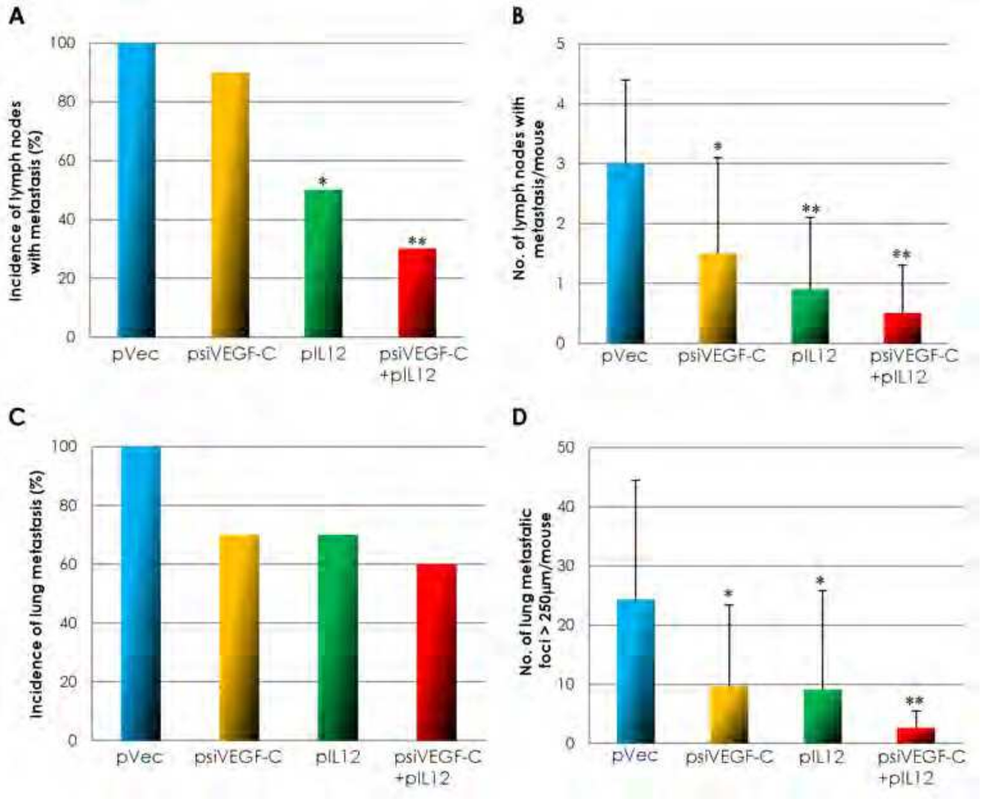

Fig. 3. Quantitative analysis of lymph node metastasis (**A** and **B**) and lung metastasis (**C** and **D**) in mice treated with pVec (control), psiVEGF-C alone, pIL12 alone, or combined psiVEGF-C+pIL12. (**A**) The incidence of lymph node metastasis was 100% in the pVec group, while the incidence was 90% in the psiVEGF-C group, 50% in the pIL12 group and 30% in the psiVEGF-C+pIL12 group; these incidences were significantly lower with pIL12 alone and pIL12 combine with psiVEGF-C. (**B**) Similarly, the number of lymph nodes with metastases per mouse was also significantly decreased in all groups receiving therapeutic treatment. (**C**) The incidence of lung metastasis tended to decrease in all therapeutic groups, but the decrease was not statistically significant. (**D**) However, the number of lung metastatic nodules >250 μm was significantly lower in all groups receiving therapeutic treatment. Data represent mean ± SD. *P<0.05; **P<0.01

3.3 Angiogenesis as measured by microvessel density

The immunohistochemical appearance of microvessels immunopositive for CD31, which is specific for the endothelium of blood vessels, is represented in Figures 4A and B. Tumor angiogenesis, as determined by the number of stained microvessels within the tumors themselves, was significantly lower in all therapeutic groups when compared to the pVec control group (Figure 5A).

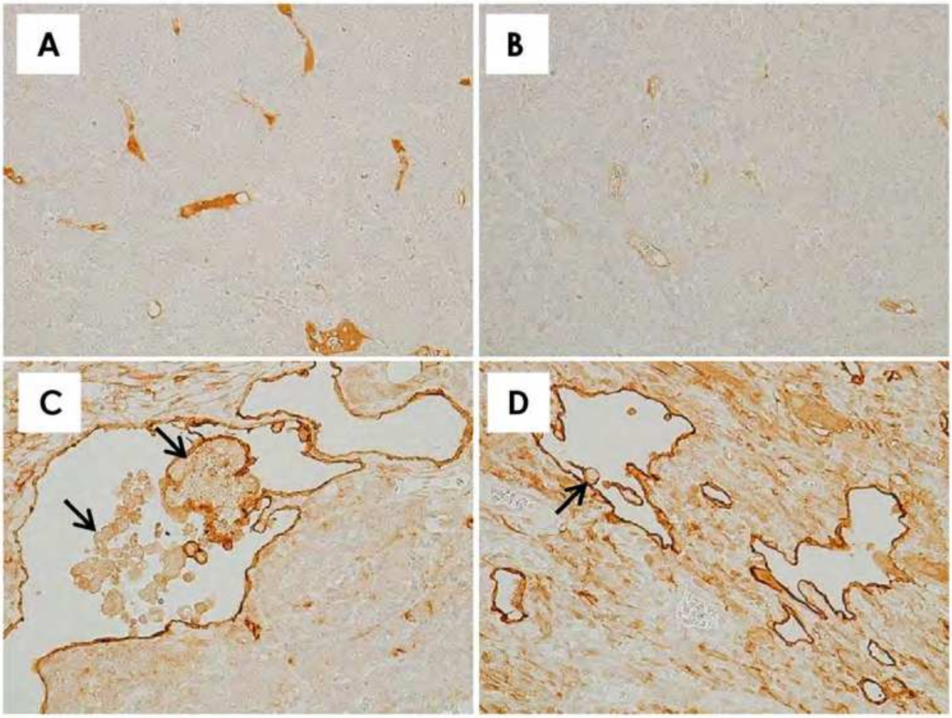

Fig. 4. Immunohistochemical analysis of angiogenesis (**A** and **B**) and lymphangiogenesis (**C** and **D**) in mammary tumors transfected with pVec (control), psiVEGF-C alone, pIL12 alone, or combined psiVEGF-C+pIL12. (**A**) A section representative of control tumors show a higher density of well-developed CD31-positive microvessels, whereas in tumors transfected with psiVEGF-C alone, pIL12 alone, or combined psiVEGF-C+pIL12 (**B**), few immunopositive vessels are seen. (**C**) Lymphatic vessels were often dilated and frequently contained migrating tumor cells within the lumina (arrows, pVec-transfected tumor). (**D**) The numbers of lymphatic vessels containing intralumenal tumor cells were lower in tumors transfected with psiVEGF-C alone, pIL12 alone, or combined psiVEGF-C+pIL12 (arrow). **A** and **B**, anti-CD31 immunohistochemistry; **C** and **D**, anti-podoplanin immunohistochemistry. Magnification: **A-D**, x400.

3.4 Dilated lymphatic vessels

The relative decrease in the number of dilated lymphatic vessels containing intraluminal tumor cells indicates migratory inhibition of cancer cells via the lymphatics of the tumor. Anti-podoplanin staining of the lymphatic microvessels in mammary tumors is demonstrated in Figures 4C and D. In all groups, these lymphatic microvessels were well developed in the outer, superficial layers of the mammary tumors in a somewhat hexagonal network pattern. We frequently observed tumor cells within the lumina of dilated lymphatic vessels in tumors of both control (Figure 4C) and treated animals (Figure 4D). However, as shown in Figure 5B, the number of lymphatic vessels carrying detached cancer cells was lower in both the pIL12 and psiVEGF-C + pIL12 groups, but this difference was statistically significant only in the mice receiving pIL12 alone. The data from mice treated with psiVEGF-C alone showed large variations.

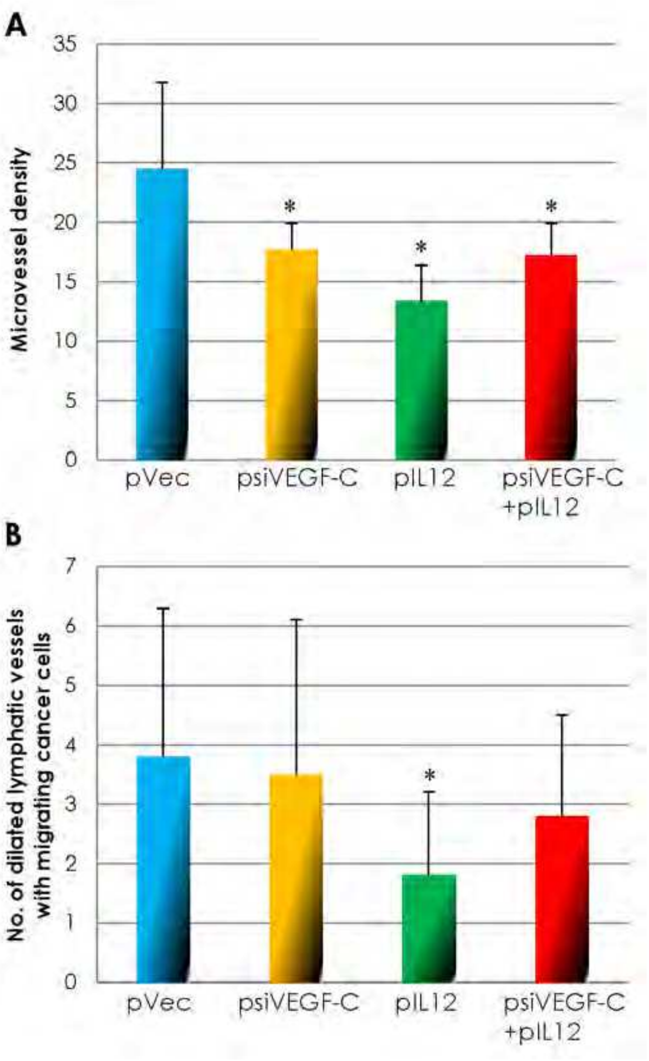

Fig. 5. Microvessel density (**A**) and frequency of lymphatic vessels containing migrating cancer cells (**B**) from tumors transfected with pVec (control), psiVEGF-C alone, pIL12 alone or combined psiVEGF-C+pIL12. (**A**) Microvessel density was significantly lower in tumors of mice receiving therapeutic vectors compared to the pVec control. (**B**) The number of lymphatic vessels containing intraluminal cancer cells was lower in the tumors transfected with pIL12 alone and combined psiVEGF-C+pIL12 as compared with the pVec controls, but significant differences were observed in the pIL12 alone group only. Data represent mean ± SD. $^*P<0.05$.

4. Discussion

Since metastasis seems to be the biggest prognostic factor for lethality in most cancers, finding therapies that control or totally inhibit tumor spread is of paramount importance. A variety of mechanisms may contribute to the dissemination of primary cancer cells: local tissue invasion, systemic metastasis via tumor blood vessels to distant organs, and lymphatic metastasis via tumor lymphatic vessels to the sentinel lymph node, distal lymph nodes, and from there to distal organs. In general, the most common pathway of initial dissemination is via the lymphatics, with patterns of spread via afferent ducts [30]. The lymphatic capillaries present in tissues and tumors provide entrance into the lymphatic system, allowing cancer cell migration to the lymph nodes. In this study, lymph node metastasis was significantly decreased by exposure to vectors expressing siVEGF-C, IL-12, or a combination vector expressing both. We also observed a significant decrease in the number of lymphatic vessels containing tumor cells intraluminally in tissues from mice receiving pIL12 alone and the combination of psiVEGF-C/pIL12, suggesting an inhibitory effect on migration into tumor lymphatic vessels that supports the significant reduction in lymph node metastasis in these groups.

VEGF-C expression has been shown to correlate with lymph node metastasis in a variety of human cancers, including breast [6,31]. In many animal models of cancer, VEGF-C has been shown to enhance tumor lymphangiogenesis, the metastatic spread of tumor cells to lymph nodes and, in some cases, to distant organs [32]. Downregulation of VEGF-C using siRNA has been shown to reduce lymph node and lung metastases in murine mammary cancer models [13,22]. In 2009, an endogenous soluble isoform of VEGFR-2 (sVEGFR-2) that sequesters VEGF-C was identified and shown to be the first endogenous specific inhibitor of lymphatic vessel growth [33]. Endogenous sVEGFR-2 is a truncated form of 230 kDa membrance-bound form of VEGFR-2 resulting from alternative splicing. Subsequently, it has been shown that endogenous sVEGFR-2 suppresses tumor growth and lymph node metastasis in a mouse mammary cancer model [34]. This molecule significantly inhibits lymphangiogenesis, but not angiogenesis, in mammary tumor tissues [34]. In addition, VEGFR-3, the VEGF-C receptor, is predominantly expressed on lymphatic endothelial cells [35], and VEGF-C-dependent activation of VEGFR-3 stimulates the growth of lymph endothelial cells and lymphatics [36]. Blockade of VEGFR-3 signaling by soluble VEGFR-3 inhibits lymphangiogenesis and lymph node metastasis in experimental animal cancer models [11,37,38].

Cancer cells metastasize to distal sites via the vascular system as well as via the lymphatic system. Significant decreases in microvessel density were observed in the tumors we injected with psiVEGF-C, pIL12, and the combination vector. VEGF-C has been reported to stimulate angiogenesis under certain experimental conditions [39]. The biosynthesis of VEGF-C involves proteolytic processing that gives intermediate forms along with a 21kDa mature form [36]. The intermediate forms predominantly bind to VEGFR-3, whereas the mature form can bind to both VEGFR-3 and VEGFR-2 to induce angiogenesis [36], which explains the inhibition of angiogenesis observed with exposure to psiVEGF-C [36,40]and which is in agreement with our previous VEGF-C siRNA experiment [13].

In contrast, IL-12 has also been shown to strongly inhibit angiogenesis in mouse corneal neovascularization [20] and in several tumor models [19,21]. IL-12 itself has no direct action on vascular endothelial cells; however, IL-12 induction of IFNγ can apparently suppress angiogenesis on Matrigel-cultured human umbilical vein endothelial cells [19]. But IFNγ does not seem the only player in angiogenesis inhibition; the cytokine IP-10 (IFNγ-inducing protein-10) has also been reported to be a potent antiangiogenic factor *in vivo* [41]. The exact mechanism of angiogenic suppression induced by IL-12 is therefore another avenue to explore in tumor therapeutics.

And the means of administration may also affect the efficacy of IL-12 as an anti-angiogenic/anti-metastatic agent. In a phase I clinical trial, recombinant IL-12 stimulated significant immunological activity in cancer patients [42]. However, despite initial enthusiasm for recombinant IL-12 as a potential anti-tumor agent, severe systemic toxicities have repeatedly been reported in clinical trials, limiting its use [43,44]. In contrast to direct cytokine administration, *IL-12* gene therapy using an adenoviral vector in animal cancer models has been shown to be as effective as protein exposure, but avoids the systemic toxicity seen in human trials [45-47]. One of the major advantages of gene transfer compared with the administration of recombinant proteins is the quicker achievement of steady-state levels of circulating protein [48]; administration of recombinant proteins leads first to a concentration peak, which may be within the zone of toxicity and responsible for adverse effects, followed by a rapid fall to sub-therapeutic levels.

The administration of either psiVEGF-C, pIL12, or a combination of both psiVEGF-C + pIL12 vectors significantly suppressed tumor growth and metastasis in our immunocompetent metastatic mammary cancer model. Since Carter *et al.* have reported the chance of tumor recurrence and/or metastasis increases dramatically once breast cancers reach 4 cm or larger [49], this reduction in tumor volume induced by decreasing VEGF-C and increasing IL-12 expression could be clinically significant; the fact that the treatment with a combined psiVEGF-C and pIL12 vector showed an enhanced inhibitory effect not only on tumor growth but also on metastasis is of particular importance when considering therapeutic strategies in breast cancer treatment. In conclusion, treatment with psiVEGF-C and pIL12 exerted combinational effects for suppression of tumor growth and metastasis in mouse mammary cancer model, suggesting a potentially significant clinical option in the treatment of metastatic human breast cancer.

5. Abbreviations

BrdU, 5-bromo-2′-deoxyuridine; *EF-1α/HTLV-1*, elongation factor –1α/human T cell leukemia virus type 1; *H&E*, hematoxylin and eosin; *IFNγ*, interferon-γ; *IL-12*, interleukin-12; *IP-10*, IFNγ-inducing protein-10; *MMTV*, mouse mammary tumor virus; *shRNA*, short hairpin RNAs; *siRNA*, short interfering RNA; *VEGF-C*, vascular endothelial growth factor-C; *VEGFR*, vascular endothelial growth factor receptor

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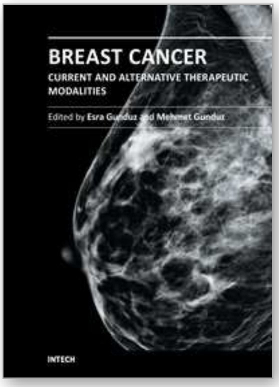

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