

High Efficacy of a *Listeria*-Based Vaccine against Metastatic Breast Cancer Reveals a Dual Mode of Action

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Abstract

Most cancer vaccines induce CTL responses to tumor-associated antigens (TAA). Killing of tumor cells occurs through TAA-specific CTL-mediated cytolysis. Here, we show that one preventive followed by two therapeutic immunizations with an attenuated *Listeria monocytogenes* (LM)-based vaccine eradicates all metastases and almost the entire primary tumor in the syngeneic, aggressive mouse breast tumor model 4T1. We provide strong evidence that this is due to the combined result of direct kill by *Listeria* infecting the tumor cells and by CTL responses against *Listeria* antigens. We showed by electron microscopy that LM expressing truncated listeriolysin O (LLO) and amino acid fragments 311 to 660 of TAA Mage-b (LM-LLO-Mage-b₃₁₁₋₆₆₀) and the control strain LM-LLO infect tumor cells *in vitro* and *in vivo*. *In vitro* data indicate that tumor cell death occurs through activation of NADP⁺ oxidase and increased intracellular Ca²⁺ levels, both resulting in the production of high ROS levels. Because both LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ showed equally strong efficacies *in vivo*, we concluded that LM-LLO was crucial and Mage-b was of less importance. We found strong CTL responses to LM-LLO in the spleen, and depletion of CD8 T cells *in vivo* resulted in significant tumor regrowth (52%) in LM-LLO-vaccinated mice, indicating that LM-LLO-specific CTL indeed partially contributed to tumor cell kill *in vivo*. This dual mode of action of a *Listeria*-based vaccine has not been described before and may provide new directions in the development of more effective vaccines against metastatic breast cancer. [Cancer Res 2009;69(14):5860–6]

Introduction

Breast cancer is the most common cancer among women around the world (1), and 30% to 40% of the women diagnosed with breast cancer will progress to metastatic disease (2). Current treatment options for metastatic cancer includes surgery followed by chemotherapy or radiation and/or adjuvant therapy (3). Although first-line endocrine therapy with tamoxifen or the newer third generation aromatases is promising (4), the cure rate of metastatic breast cancer is low (5). In previous studies, we found evidence that vaccination with Mage-b DNA was effective against

metastases in various metastatic mouse breast tumor models (6, 7). Mage is an attractive tumor-associated antigen (TAA) because it is expressed in >90% of all breast cancers but not in normal cells (8). To further improve the vaccine efficacy of Mage-b, we used an attenuated *Listeria monocytogenes* (LM) as DNA delivery system. LM is an intracellular pathogen that delivers the vaccine antigen directly into APCs such as macrophages with high efficiency (9). Cell entrance of macrophages by LM occurs through active phagocytosis, and the LM escape into the host cytosol by perforating the phagosomal membrane through the action of a cytolysin, listeriolysin O (LLO; refs. 10, 11). Once in the cytosol, the vaccine antigen produced by the LM is processed and presented as short peptides via the MHC class I and class II pathways, generating both CD4 and CD8 T-cell responses (12). Killing of tumor cells occurs through CD8 T cells. Previous studies have shown that TAA Her2/neu, expressed by an attenuated LM as fusion protein with LLO, is effective against primary tumors in a syngeneic mouse breast tumor model NT-2 (13). LLO, required for the establishment of intracellular infections (14, 15), also improves immunogenicity of poor immunogenic antigens (13).

In the study presented here, we show that one preventive followed by two therapeutic immunizations with LM-LLO-Mage-b₃₁₁₋₆₆₀ completely eradicates the metastases and reduces the primary tumors by 90% in a poorly immunogenic metastatic mouse breast tumor model 4T1. Our *in vitro* and *in vivo* data strongly suggest that this is due to infection of the tumor cells with *Listeria* bacteria, resulting in tumor cell kill by high ROS levels and by *Listeria*-specific CTL. These results point the way toward novel approaches in the use of *Listeria* vaccines as antitumor agents.

Materials and Methods

Mice. Normal female BALB/c mice (3 mo old) were obtained from The Jackson Laboratory and maintained in the animal husbandry facility of the Pacific Medical Center Research Institute according to the Association and Accreditation of Laboratory Animal Care guidelines.

Plasmids and LM. The LM-LLO-Mage-b₃₁₁₋₆₆₀ was developed in our laboratory (16). The *Listerial* pGG-34 plasmid, expressing the positive regulatory factor A (prfA) and LLO, was developed in the laboratory of Yvonne Paterson, University of Pennsylvania (17, 18). The LM-LLO used in this study is attenuated, i.e., the coding region for the COOH terminal part of the LLO (cytolytic domain that binds cholesterol in the membranes) protein has been deleted, but the proline, glutamic acid, serine, and threonine (PEST) sequence is still present. Mutations have been introduced into the prfA gene (expressed by the pGG34 vector), which reduced the pathogenicity of the LM (13). pcDNA3.1-Mage-b/V5 was developed in our laboratory (6). Mouse granulocyte macrophage colony-stimulating factor plasmid (pCMV-GM-CSF) was provided by Dr. Stephen Johnston (Center for Innovations in Medicine, Biodesign Institute at Arizona State University; ref. 19).

Cells and cell culture. The 4T1 cell line, derived from a spontaneous mammary carcinoma in a BALB/c mouse (20), was cultured in DMEM supplemented with 10% fetal bovine serum, 1 mmol/L mixed nonessential

Note: Supplementary data for this article are available at Cancer Research Online (<http://cancerres.aacrjournals.org/>).

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amino acids, 2 mmol/L L-glutamine, insulin (0.5 HSP units/mL), penicillin (100 units/mL), and streptomycin (100 µg/mL).

Immunization and tumor challenge. Three different immunization protocols have been tested in this study: (a) three preventive vaccinations given 1 wk apart (days 1, 8, and 15) with tumor challenge (10^5 cells injected into a mammary fat pad) at 10 d after the last immunization (day 25); (b) one preventive vaccination, followed by tumor challenge at day 5, with two therapeutic vaccinations at days 8 and 15; or (c) three therapeutic vaccinations given 3 d after tumor challenge. Injections of $0.1 \times LD_{50}$ (10^7 bacteria) of LM-LLO-Mage-b₃₁₁₋₆₆₀, the control vector LM-LLO, or saline was given i.p. Fourteen to 18 d after tumor challenge, the mice were euthanized and analyzed for tumor weight, frequency, and location of metastases, as well as for immunologic responses in the spleen. Primary tumors extend to the chest cavity lining and metastases (visible by the naked eye as nodules) predominantly to the mesenteric lymph nodes and less frequently to the diaphragm, portal liver, spleen, and kidneys (16).

CD8 depletion *in vivo*. CD8 T cells were depleted in 4T1 tumor-bearing mice with 0.5 mg of anti-CD8 antibodies 2.43 (18) on days 3, 7, 8, 9, 14, 15, and 16, whereas one preventive and two therapeutic immunizations with LM-LLO were given at days 1, 8, and 15 and tumor challenge at day 5. Mice were euthanized and analyzed for tumor weight and frequency of metastases 14 d after tumor challenge. The antibodies were purchased from BioXCell. This antibody has been shown by many investigators to specifically deplete only CD8 T cells by >95% (13). As control, isotype-matched rat antibodies against HRPN were used (13, 17).

***In vitro* analysis of immune responses against Mage-b and *Listeria*.** Spleen cells were isolated from vaccinated and control mice with 4T1 tumors and metastases. To detect Mage-b-specific immune responses, 2×10^5 cells from spleens were restimulated with 5×10^4 autologous bone marrow (BM) cells (transfected with pcDNA3.1-Mage-b plasmid DNA and pCMV-GM-CSF plasmid DNA; 1 µg of each plasmid DNA per 5×10^6 BM cells), using the Nucleofector kit of AMAXA. To detect *Listeria*-induced immune responses, 5×10^4 autologous BM cells were infected with 10^3 LM-LLO for 1 h and subsequently treated with gentamicin. Two days later, the frequency of IFN-γ-producing cells was determined by ELISPOT for both restimulation assays according to standard protocols (PharMingen), using an ELISPOT reader (CTL Immunospot S4 analyzer, Cellular Technology Ltd.). Spleen cells were depleted for CD8 T cells using magnetic bead depletion techniques according to the manufacturer's instructions (Miltenyi Biotec, Inc.). Fluorescence-activated cell sorting analysis showed that ≥90% of all CD8 T cells were depleted.

Infection of tumor cells *in vitro*. The infectivity rate of the tumor cell lines was assessed *in vitro*. Cells (5×10^5 /mL) were infected with 10^8 (per well) of LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀ for 1 h at 37°C in culture medium, as described above. After incubation with gentamicin (50 µg/mL) for 1 h (killing all extracellular *Listeria* bacteria), cells were washed with PBS and lysed in sterile water and serial dilutions were plated onto LB agar to determine the infection rate the next day or analyzed by electron microscopy (EM) using a Philips Tecnai 10 Electron Microscope (21, 22).

Infection of tumor cells *in vivo*. BALB/c mice were injected with 10^5 4T1 tumor cells in a mammary fat pad and, 10 d later, were injected i.p. with the usual immunization dose, i.e., $0.1 \times LD_{50}$ (10^7 CFU) of LM-LLO-Mage-b₃₁₁₋₆₆₀. On the next day, mice were euthanized and tumors and metastases were analyzed by EM for the presence of *Listeria* bacteria.

Evaluation of cell death. Death of tumor or normal cells induced by LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀ was determined *in vitro* as follows. 4T1 or MCF7 cells (3×10^3) plated on 96-well plates were infected with 10^6 (per well) of LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀ for 3 h at 37°C. Gentamicin (50 µg/mL) was added until live and dead cells were counted using trypan blue staining on the next day. Recombinant LLO or LLOΔPEST (LLO without PEST sequence; 100 ng/mL) were added in 4T1 cell cultures. Cell death was evaluated as described above. Trolox (100 µmol/L), apocynin (500 µmol/L), diphenylene iodonium (DPI; 50 nmol/L), or membrane permeable Ca²⁺-chelator BAPTA (2 µmol/L) were concomitantly cultured with the *Listeria* bacteria.

Immunostaining. Immunostaining was performed in 4T1 cultures grown on glass-bottomed dishes with or without 10^8 bacteria of LM-LLO or

LM-LLO-Mage-b₃₁₁₋₆₆₀ for 2 h. Subcellular localization of the p47^{phox} subunit of NADPH oxidase was evaluated in cultures fixed with 4% paraformaldehyde for 20 min on ice. After preincubation in blocking buffer (0.01% PBS, 2% goat serum, 0.2% Triton-X, 0.1% bovine serum albumin) for 30 min, the cultures were incubated with a 1:500 dilution of mouse anti-p47^{phox} antibody (BD Biosciences, Transduction Laboratories). Primary antibody binding was visualized with a 1:400 dilution of Alexa Fluor 555-conjugated antimouse IgG (Molecular Probes; Invitrogen). Fluorescence microscopy was performed on a TE2000 Nikon inverted microscope with a Photometrics and MetaMorph software (MolecularDevices).

Detection of *Listeria* and Mage-b proteins in infected tumor cells. 4T1 tumor cells (5×10^5) were infected with LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀ (10^8 bacteria), then treated with gentamicin (50 µg/mL) for 2 h, washed thrice with PBS, and analyzed by Western blotting. LLO (containing PEST motif) and LLO fused with Mage-b₃₁₁₋₆₆₀ were detected with anti-PEST antibodies (dilution, 1:1,000).

Imaging of ROS and Ca²⁺. 4T1 or MCF7 tumor cells (2×10^5 /mL) grown on glass-bottomed dishes were infected with 10^6 of LM. Two hours later, cells were loaded with 5 µmol/L 5- (and -6)-carboxy-2',7'-difluorodihydrofluorescein diacetate for intracellular ROS, 100 nmol/L Mitotracker Red CM-H₂XROS for mitochondrial ROS, or 10 µmol/L calcium green-1 (Molecular Probes; Invitrogen) for intracellular free Ca²⁺ in HBSS for 25 min at 37°C and washed thrice with HBSS. The signals of ROS or Ca²⁺ were observed at room temperature on the stage of a TE2000 Nikon inverted microscope with a Photometrics and Coolsnap HQ CCD camera controlled by MetaMorph software (Molecular Devices).

Results

Combined preventive and therapeutic immunization completely eradicates metastases. In a previous study, we developed a LM-LLO-Mage-b₃₁₁₋₆₆₀ vaccine (16). After the combination of two preventive and one therapeutic immunization, a significant effect was observed on the metastases but not on the primary tumors (16). In the current study, we initially aimed to further improve our vaccination protocol. We reasoned that because the vaccine effect on the tumor was likely due to immune responses, preventive immunizations only (tumor challenge at 10 days after the last immunization) should increase the vaccine efficacy, but this was not the case. A moderate but significant effect was observed on the metastases by the LM-LLO-Mage-b₃₁₁₋₆₆₀ vaccine, but again, no effect was observed on the primary tumors (Fig. 1A). A similarly modest effect was also observed after three therapeutic immunizations (Supplementary Fig. S1). However, one preventive immunization, followed by two therapeutic immunizations, completely eradicated metastases, and the growth of primary tumors was reduced by almost 90% (Fig. 1B). Moreover, inexplicably, the control strain LM-LLO was almost as effective as LM-LLO-Mage-b₃₁₁₋₆₆₀.

To find an explanation for this difference in vaccine efficacy, we compared Mage-b-specific CTL responses after the three preventive immunizations with the more successful combination of one preventive and two therapeutic immunizations. Restimulation of spleen cells of vaccinated and control mice, bearing 4T1 tumors and metastases, with autologous BM cells expressing Mage-b, showed strong Mage-b-specific CD8 T-cell responses after both vaccination strategies (Fig. 1C, *i* and *ii*), suggesting that CTL-mediated tumor cell kill was not the only cause of this strong *in vivo* effect in the combination strategy (one preventive followed by two therapeutic immunizations). As expected, three therapeutic immunizations showed reduced Mage-b-specific immune responses in the spleen (Supplementary Fig. S1), likely induced by the primary tumors. However, the similar *in vivo* efficacies of the

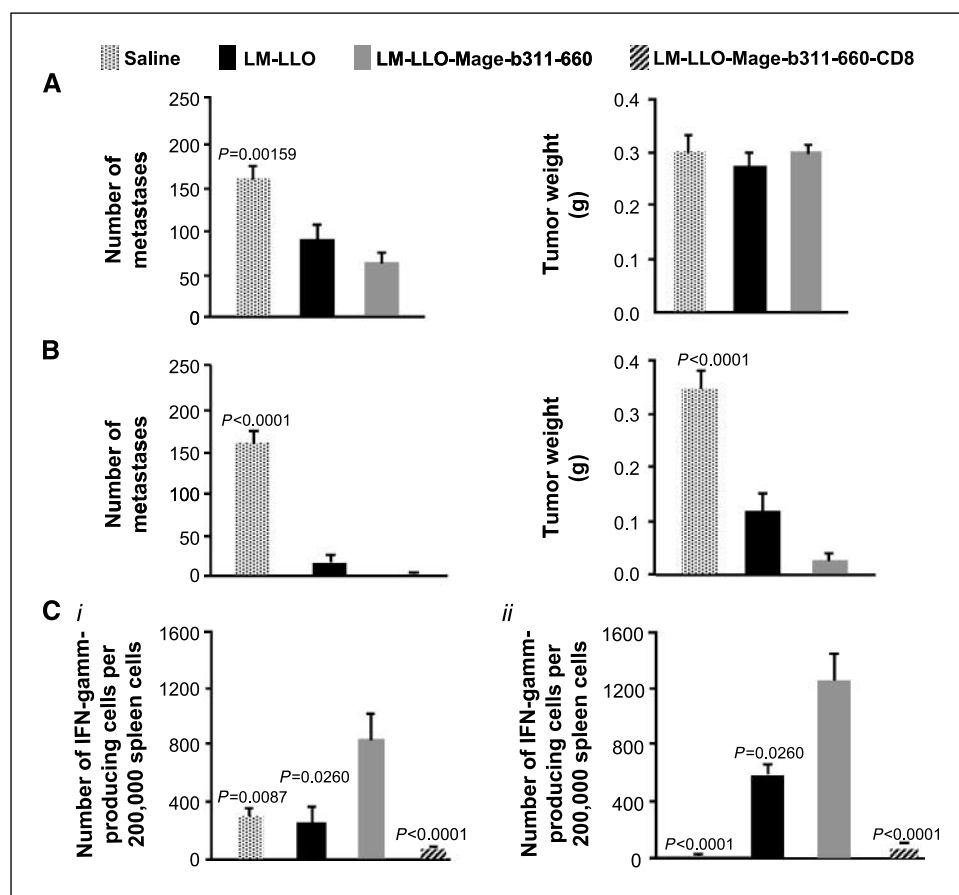


Figure 1. Effect of LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ *in vivo* and *in vitro*. The frequency of metastases and tumor weight was determined after three preventive immunizations (A) and after a combination of one preventive and two therapeutic immunizations (B). Also Mage-b-specific immune responses (C) were analyzed after three preventive immunizations (i) and after the combination of one preventive and two therapeutic immunizations (ii) by ELISPOT. For this purpose, spleen cells were pooled per group, restimulated with BM cells (transfected with pcDNA3.1-Mage-b and pCMV1-GM-CSF), and analyzed for the production of IFN γ 72 h later. The involvement of CD8 T cells was determined by negative depletion, using magnetic beads with anti-CD8 antibodies. Controls such as BM cells transfected with pcDNA3.1-Mage-b or pCMV1-GM-CSF or nontransfected BM cells did not produce IFN γ (data not shown). Columns, average of two to three independent experiments, $n = 5$ mice per group; bars, SE. Significant differences between Mage-b and other groups were analyzed using Mann-Whitney test. $P < 0.05$ is significant.

control and vaccine strain in the combined immunization suggested that the *Listeria* bacteria itself may have an effect on the tumor cells, a hypothesis that we further pursued as described below.

Listeria infects and kills tumor cells. To analyze whether the *Listeria* bacteria could have a direct effect on tumor cells, 4T1 tumor cells were cultured with the LM-LLO-Mage-b₃₁₁₋₆₆₀ or with the control strain LM-LLO *in vitro*. LM-LLO-Mage-b₃₁₁₋₆₆₀ and LM-LLO not only infects but also kills 4T1 tumor cells with high efficiency in the complete absence of immune cells (Fig. 2A). A similar result was observed with a human breast tumor cell line MCF7 (Fig. 2A). Although the infection rate of MCF7 was five times higher than of 4T1 tumor cells, i.e., after 1 hour of incubation, 20% of the 4T1 and 100% of the MCF7 tumor cells were infected (Fig. 2A) and after 2 to 3 hours of incubation, the infection rate of both tumor cell lines was 100% (data not shown). Interestingly, LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ killed the tumor cells (4T1 and MCF7) with the same efficacy. Therefore, we concluded that LM-LLO and not Mage-b₃₁₁₋₆₆₀ mediated the direct tumor cell kill *in vitro*.

Using EM, we showed the presence of *Listeria* bacteria in the tumor cells both *in vitro* (cultured 4T1 and MCF7 tumor cell lines) and *in vivo* (4T1 metastases and primary tumor; Fig. 2B).

Mechanism(s) of tumor cell kill by *Listeria*. We then asked which pathways could be triggered by LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ resulting in tumor cell death. Bacteria can trigger apoptosis through a large variety of mechanisms that include the secretion of protein synthesis inhibitors, pore-forming proteins, or molecules responsible for the activation of the endogenous death machinery

in infected cells (23). It is known that LM activates NADPH oxidase in macrophages and neutrophils (24–26). Here, we show that LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ induce the death of 4T1 and MCF7 tumor cells through the activation of NADPH oxidase and subsequent production of ROS (Fig. 3A, i). Trolox, a scavenger of OH \cdot radicals, and apocynin or DPI, both selective inhibitors of NADPH oxidase, significantly decreased LM-LLO-induced and LM-LLO-Mage-b₃₁₁₋₆₆₀-induced cell death of 4T1 or MCF7 tumor cells (Fig. 3A, ii), which shows the involvement of NADPH oxidase-mediated ROS in tumor cell death. Accordingly, we examined whether ROS was produced in tumor cells upon *Listeria* infection. Live cell microscopy with H₂DFFDA or CM-H₂XRos revealed that cytosolic ROS were produced through activated NADPH oxidase and that mitochondrial ROS were produced as well (Fig. 3B). Our findings collectively imply that NADPH oxidase-mediated ROS production and subsequent mitochondrial dysfunction contribute to LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀-induced tumor cell death.

It was obvious that trolox and/or apocynin could only prevent 50% of the LM-LLO-induced cell death (Fig. 3A, ii). This suggests that, in addition to NADPH oxidase-mediated ROS, other pathway(s) are involved in tumor cell death. It has been shown by others that LLO is involved in the rapid increase in intracellular Ca²⁺ levels in a macrophage cell line, J774 (27). Therefore, we analyzed intracellular Ca²⁺ levels in 4T1 cells after the addition of LM-LLO. Indeed, LM-LLO increased intracellular Ca²⁺ levels, as shown with Ca²⁺ green-1 (Fig. 3C, i). BAPTA, a membrane permeable Ca²⁺ chelator, reduced mitochondrial ROS detected with CM-H₂Ros (Fig. 3C, ii) and LM-LLO-induced tumor cell death by 50% (Fig. 3C, iii). Moreover, BAPTA combined with apocynin very effectively

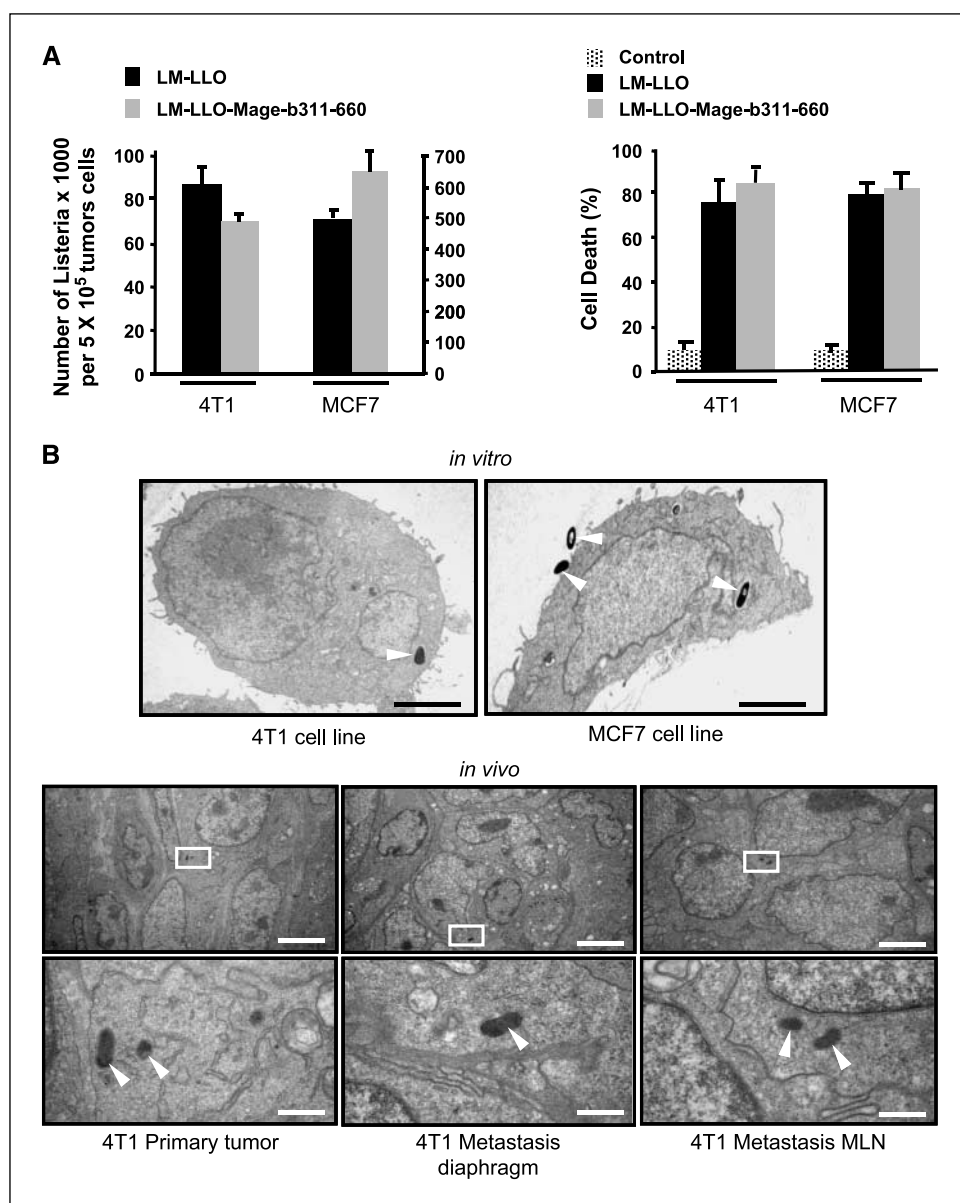
reduced mitochondrial ROS detected with CM-H₂ROS (Fig. 3C, ii) and prevented the LM-LLO-induced cell death by 80% (Fig. 3C, iii). These results imply that NADPH oxidase and excessive intracellular calcium contribute to tumor cell death upon LM-LLO infection causing mitochondrial failure.

As concluded earlier, LM-LLO, but not Mage-b₃₁₁₋₆₆₀, is involved in direct tumor cell kill. Thus, we analyzed the involvement of LM-LLO in tumor cell kill in more detail. Because LLO is required to establish intracellular infections (14, 15), we were wondering whether LLO could be involved in tumor cell death. A sequence rich in PEST at the amino terminus of LLO is thought to control the production of LLO (28). Therefore, we analyzed the effect of LLO protein with and without PEST on 4T1 tumor cells *in vitro*. Incubation of 4T1 tumor cells with LLO protein killed 80% to 90% of the 4T1 tumor cells, whereas LLO Δ pest did not induce tumor cell death (Fig. 3D). These results indicate that the PEST sequence is involved in tumor cell death. Moreover, apocynin was able to prevent 50% of the 4T1 tumor cell death induced by LLO protein

(Fig. 3D), suggesting that PEST is involved in the activation of NADPH oxidase. LLO protein did not induce an increase in intracellular Ca²⁺ levels (data not shown).

Expression of Mage-b and *Listerial* proteins by tumor cells and immunologic consequences. As shown above, LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ are able to infect and kill tumor cells in the complete absence of immune cells *in vitro*. However, infection of the tumor cells with *Listeria* bacteria does have consequences for the immune system *in vivo*. We show here that infection of tumor cells *in vitro* with LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀ bacteria resulted in overexpression of *Listerial* proteins and Mage-b₃₁₁₋₆₆₀ (in addition to relatively low levels of natural Mage-b; ref. 16; Fig. 4A). In addition, macrophages will be infected, as well, by LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀, resulting in strong CTL responses against both Mage-b₃₁₁₋₆₆₀ (Fig. 4B) and the highly immunogenic *Listerial* proteins, as shown here *in vitro* (Fig. 4C). Because the combined (preventive/therapeutic) vaccination with LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ eradicated metastases and primary tumors

Figure 2. *Listeria* infects and kills tumor cells. **A**, both LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ infected 4T1 and MCF7 with high efficiency after 1 h of infection. Experiments were performed in triplicates and repeated thrice. *Columns*, average of three infection experiments; *bars*, SE. Both LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ killed 4T1 and MCF7 with the same efficiency (unpaired *t* test, *P* > 0.05). In this experiment, 4T1 tumor cells were incubated with the *Listeria* bacteria for 3 h and then treated with gentamicin. On the next day, dead and alive tumor cells were determined with trypan blue. From each sample, nine fields were blindly analyzed by two different investigators. Experiments were performed in triplicates and repeated thrice. *Columns*, average of three experiments; *bars*, SE. **B**, EM analysis shows the *Listeria* bacteria (LM-LLO-Mage-b₃₁₁₋₆₆₀) inside 4T1 and MCF7 tumor cells after 1-h infection *in vitro*. *Bar*, 200 μ m. The *Listeria* bacteria also infected 4T1 primary tumor and metastases *in vivo* with high efficiency, as shown here after one immunization with LM-LLO-mage-b₃₁₁₋₆₆₀. *Bar*, 400 μ m (*top*) and 50 μ m (*bottom*). In this experiment, tumors and metastases of three different mice that received LM-LLO-Mage-b₃₁₁₋₆₆₀ were analyzed. Representative for the three different mice analyzed. *White arrows*, *Listeria* bacteria.



almost with the same efficiency, we concluded that most of the *in vivo* effect here was derived from LM-LLO. Depletion of CD8 T cells in mice that received one preventive and two therapeutic immunizations with LM-LLO showed an increase in tumor growth by 52% compared with LM-LLO alone (Supplementary Fig. S2), suggesting that *Listeria*-specific CD8 T cells, at least partially, contribute to tumor reduction *in vivo*. CD8 depletions did not alter the frequency of metastases, and it is possible that direct kill may play a more important role here.

Discussion

Whereas LM-based cancer vaccines are supposed to exert their effect through killing of tumors cells by CTL responses to TAAs, our present work shows that this is not necessarily the only and most efficient mechanism. Here, we show a dramatic effect of a *Listeria*-based vaccine on metastases and primary tumor after one preventive followed by two therapeutic immunizations in a highly

aggressive and poorly immunogenic mouse model 4T1. We provide strong evidence that efficient tumor cell kill can be achieved through a dual mode of action by LM involving both direct kill and CTL responses to *Listeria* antigens. EM studies showed that both the vaccine (LM-LLO-Mage-b₃₁₁₋₆₆₀) and control strain (LM-LLO) infect tumor cells *in vitro* and *in vivo* and that both kill tumor cells *in vitro* through the generation of high levels of ROS resulting in oxidative stress. Evidence for tumor cell kill by CTL responses to LM-LLO is based on *in vitro* and *in vivo* data. We showed *in vitro* that infection of the tumor cells with LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ resulted in high expression of *Listeria* and Mage-b proteins and strong *Listeria*-specific and Mage-b-specific CTL responses in the spleen of tumor-bearing vaccinated mice. However, we showed that the combined vaccination with LM-LLO and LM-LLO-Mage-b₃₁₁₋₆₆₀ eradicated metastases and primary tumors almost with the same efficiency *in vivo*, indicating that most of the *in vivo* effect was derived from LM-LLO. Depletion of CD8 T cells in LM-LLO-vaccinated mice resulted in tumor regrowth (~50%), suggesting

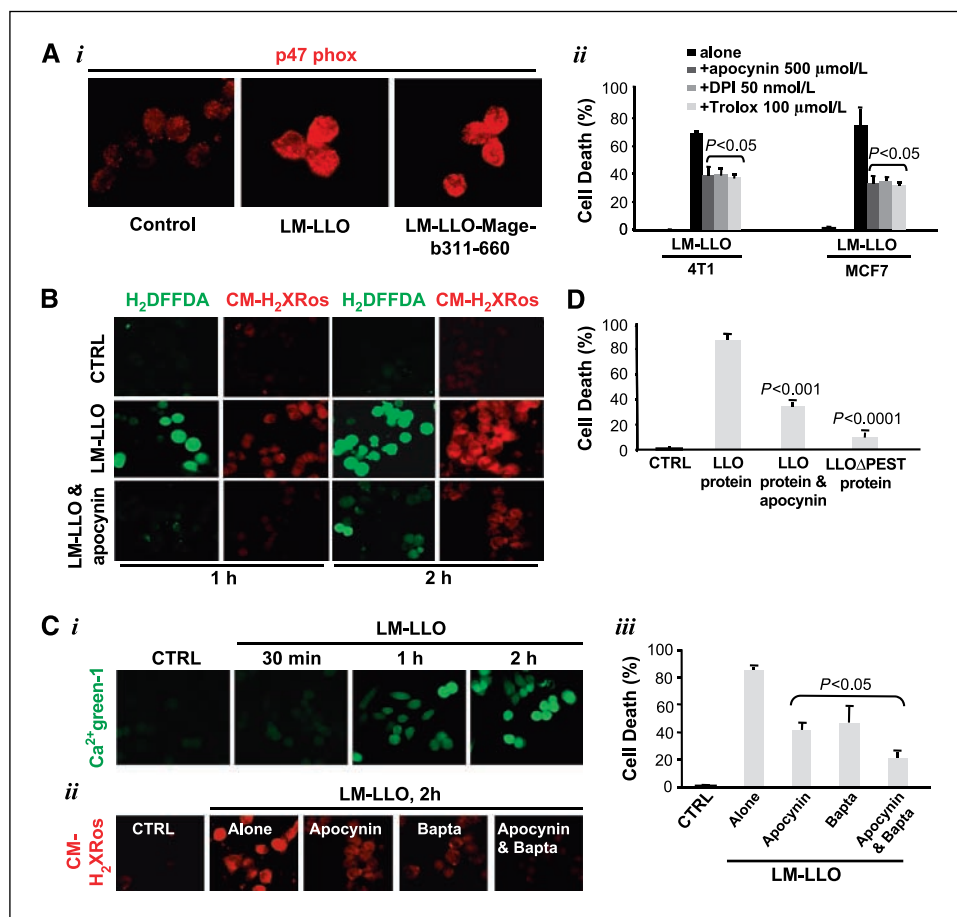
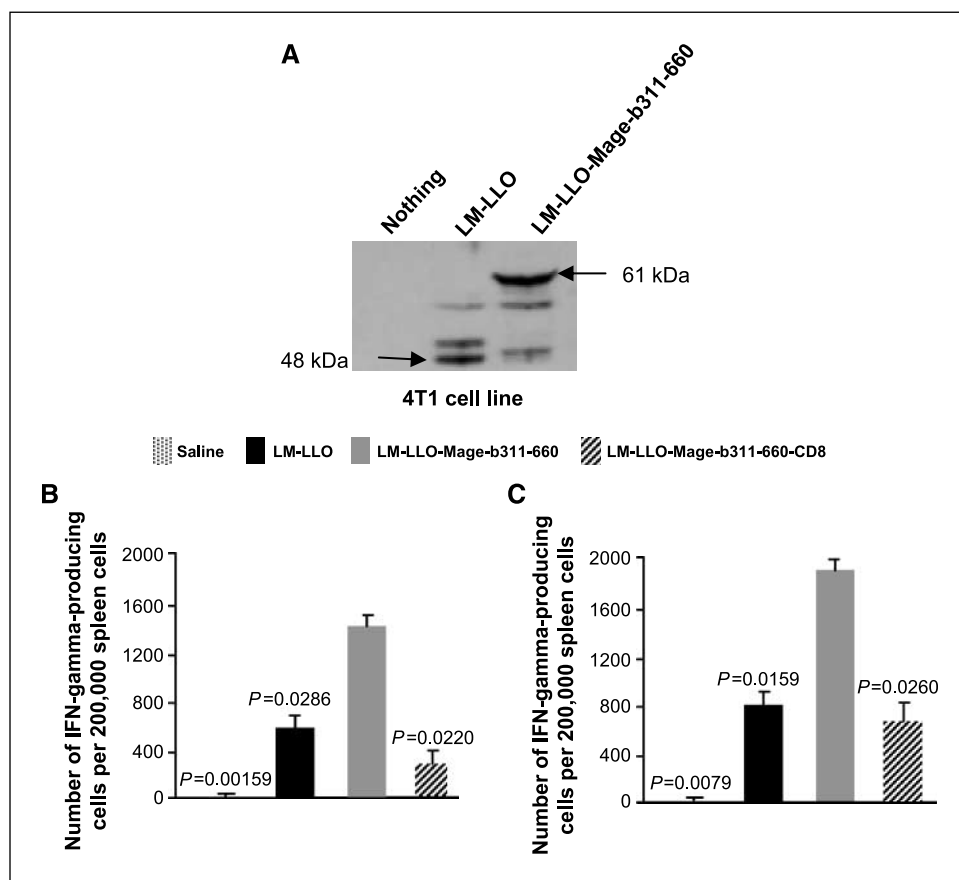


Figure 3. Mechanism(s) of tumor cell kill by LM-LLO-Mage-b₃₁₁₋₆₆₀ and LM-LLO. *A*, *Listeria*-induced tumor cell death by activation of NADPH oxidase and production of ROS. 4T1 tumor cells were incubated with LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀ for 2 h and analyzed for activation of NADPH oxidase using antibodies to p47phox (*i*). NADPH oxidase-induced cell death was prevented by apocynin, whereas ROS-induced cell death was prevented by trolox and DPI (*ii*). Significant differences were found between 4T1 tumor cells treated with inhibitors compared with untreated 4T1. Unpaired *t* test, $P < 0.05$ is significant. A similar result was observed with MCF7. *B*, prevention of *Listeria*-induced ROS with apocynin. 4T1 tumor cells were incubated with LM-LLO, in the presence or absence of apocynin, and showed decreased production of ROS with H₂DFFDA (cROS and mROS) or CM-H₂XROS (mROS). *C*, LM-LLO also induced increase in intracellular Ca²⁺ levels in 4T1 tumor cells, as shown with Ca²⁺-green-1 (*i*). LM-LLO-induced mitochondrial disruption (*ii*) in 4T1 tumor cells and subsequent tumor cell death (*iii*) could be prevented with apocynin an/or BAPTA. Whereas both apocynin and BAPTA were able to prevent tumor cell death by 50% when added separately, 80% to 90% of tumor cell death could be prevented when added combined with infected tumor cell cultures (*iii*). Significant differences were found between 4T1 tumor cells treated with inhibitors compared with untreated 4T1. Unpaired *t* test, $P < 0.05$ is significant. *D*, the PEST motif in LLO of the *Listeria* bacteria activates NADPH oxidase and is involved in tumor cell death. This could be prevented with apocynin. LLO protein (LLO) with or without the PEST motif (LLOΔPEST) was added to 4T1 cultured, and cell death was determined the next day. Significant differences between LLO protein and other groups were analyzed. Unpaired *t* test, $P < 0.05$ is significant. Experiments were performed in triplicates and repeated twice. The results presented here are the average (*Aii*, *Ciii*, *D*) or a representative (*Ai*, *B*, *Ci*, *Cii*) of two experiments performed. The error bars represent SE.

Figure 4. Expression of Mage-b₃₁₁₋₆₆₀ and *Listeria* proteins by 4T1 tumor cells. 4T1 tumor cells were incubated with LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀ for 2 h and subsequently analyzed for the expression of Mage-b₃₁₁₋₆₆₀ (fused with LLO; 61 kDa) and *Listeria* (LLO; 48 kDa) proteins by Western blotting using anti-PEST antibodies (A). Spleen cells (pooled) of vaccinated (preventive/therapeutic) and control mice bearing 4T1 metastases and primary tumors were analyzed for Mage-b-specific and *Listeria*-specific immune responses by ELISPOT using BM cells (transfected with pcDNA3.1-Mage-b and pCMV1-GM-CSF, B) and BM cells infected with LM-LLO (C), respectively. The involvement of CD8 T cells was determined by negative depletion, using magnetic beads with anti-CD8 antibodies. Columns, average of two independent experiments, $n = 5$ mice per group; bars, SE. Significant differences between Mage-b and other groups were determined. Mann-Whitney test, $P < 0.05$ is significant.



that *Listeria*-specific CTL responses were indeed, at least partially, effective against the primary tumor. CD8 depletions did not alter the frequency of metastases. It is possible that the metastases are directly killed by the *Listeria* bacteria. Because we only did CD8 depletion studies, we cannot rule out that natural killer cell responses and CD4 T-cell responses are involved, as well. Although the presence of bacteria in tumors has been recognized earlier (29–31), the direct kill and immunologic consequences, as shown with the attenuated LM in the current study, has not been reported thus far.

If *Listeria* is mediating direct tumor cell kill *in vivo*, why are normal cells not affected? Indeed, primary cultures of normal mouse or human fibroblasts were infected and killed by LM-LLO as efficiently as the tumor cells *in vitro* (Supplementary Fig. S3). However, mice that were immunized with LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀ seemed completely healthy. Analysis of the liver, spleen, and gastrointestinal tissues (known targets for LM infection) for pathologic damage after three immunizations with LM-LLO or LM-LLO-Mage-b₃₁₁₋₆₆₀ showed a few inflammatory spots (concentration of lymphocytes) in the liver only (data not shown). Also, liver functions such as AST and ALT were unaffected by the *Listeria* bacteria (Supplementary Table S1). To explain this apparent lack of effect on normal tissues, we hypothesize that *in vivo* the *Listeria* are cleared very efficiently by the immune system from normal tissues, as we have shown for the spleen in this study (3 days after infection, *Listeria* could not be cultured anymore from the spleen). At the same time, vaccine-induced immune responses are, at least, partially suppressed in the tumor environment, as we found in the draining lymph nodes of the current (data not shown) and a

previous study (16) and have also been shown by others (32). Therefore, *Listeria* bacteria in the tumor microenvironment may be protected from clearance by the immune system, but not in the normal tissues. This is in keeping with the results obtained by others reporting only flu-like symptoms of LM-LLO-based vaccines in cancer patients in phase I/phase II clinical trials (33).

In summary, our results show that different immunization strategies with LM-LLO-Mage-b₃₁₁₋₆₆₀ provide different effects on metastatic breast cancer in the highly aggressive mouse model 4T1. The combined preventive/therapeutic immunization was superior over three preventive or three therapeutic immunizations. Our results strongly suggest that this is due to the combination of direct kill and *Listeria*-specific CTL-mediated tumor cell cytotoxicity. Reduced efficacies after exclusive preventive or therapeutic immunizations may be due to vaccine-induced immune responses or direct kill as separate actions, respectively. This dual mode of action through tumor cell infection has not been described before and opens up new strategies for eradicating breast cancer effectively through the combination of direct kill and immune responses against highly immunogenic antigens rather than against weak TAA.

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References

1. Althuis MD, Singh S. Global trends in breast cancer incidence and mortality. 1973-1997. *Int J Epidemiol* 2005; 34:405-12.
2. Berkowitz N, Gupta S, Silberman G. Estimates of the lifetime direct costs of treatment for metastatic breast cancer. *Value Health* 2000;3:23-30.
3. Scart H, Cantin J, Levin M. Clinical practice guidelines for the care and treatment of breast cancer: mastectomy or lumpectomy? The choice of operation for clinical stages I and II breast cancer (summary of the 2002 update). *CMAJ* 2002;167:145-55.
4. Kurtz JE, Dufour P. Strategies for improving quality of life in older patients with metastatic breast cancer. *Drugs Aging* 2002;19:605-22.
5. Alberg AJ, Singh S. Epidemiology of breast cancer in older women: implications for future health care. *Drugs Aging* 2001;18:761-2.
6. Sypniewska RK, Hoflack L, Tarango M, et al. Prevention of metastases with a Mage-b DNA vaccine in a mouse breast tumor model: potential for breast cancer therapy. *BCRT* 2005;91:19-28.
7. Gravekamp C, Leal B, Denny A, et al. *In vivo* responses to vaccination with Mage-b, GM-CSF and thioglycollate in a highly metastatic mouse breast tumor model, 4T1. *Cancer Immunol Immunother* 2008; 57:1067-77.
8. Park JW, Kwon TK, Kim IH, et al. A new strategy for the diagnosis of MAGE-expressing cancers. *J Immunol* 2002; 79:79-86.
9. Paterson Y, Maciag P. *Listeria*-based vaccines for cancer treatment. *Curr Opin Mol Ther* 2005;7:454-60.
10. Dussurget O, Pizarro-Cerda J, Cossart P. Molecular determinants of *Listeria monocytogenes* virulence. *Ann Rev* 2004;58:587-10.
11. Gedde MM, Higgins DE, Tilney LG, Portnoy DA. Role of Lysteriolysin O in cell-to-cell spread of *Listeria monocytogenes*. *Infect Immun* 2000;68:999-1003.
12. Paterson Y, Ikonomidis G. Recombinant *Listeria monocytogenes* cancer vaccines. *Curr Opin Immunol* 1996;8:664-9.
13. Singh R, Domineicki ME, Jaffee EM, Paterson Y. Fusion of Lysteriolysin O and delivery by *Listeria monocytogenes* enhances the immunogenicity of HER-2/neu and reveals subdominant epitopes in the FVB/N mouse. *J Immunol* 2005;175:3663-73.
14. Gaillard JL, Berche P, Sansonetti P. Transposon mutagenesis as a tool to study the role of hemolysin in the virulence of *Listeria monocytogenes*. *Infect Immun* 1986;52:50-5.
15. Portnoy DA, Jacks PS, Hinrichs DJ. Role of hemolysin for the intracellular growth of *Listeria monocytogenes*. *J Exp Med* 1988;167:1459-71.
16. Kim SH, Castro F, Gonzalez D, Maciag PC, Paterson Y, Gravekamp C. Mage-b vaccine delivered by recombinant *Listeria monocytogenes* is highly effective against breast cancer metastases. *British Journal of Cancer* 2008; 99:741-9.
17. Gunn GR, Zubair A, Peters C, Pan ZK, Wu TC, Paterson Y. Two *Listeria monocytogenes* vaccine vectors that express different molecular forms of human papillomavirus-16 (HPV-16) E7 induce qualitatively different T cell immunity that correlates with their ability to induce regression of established tumors immortalized by HPV-16. *J Immunol* 2001; 167:6471-9.
18. Pan ZK, Okonomidis G, Lazenby A, Pardoll D, Paterson Y. A recombinant *Listeria monocytogenes* vaccine expressing a model tumor antigen protects mice against lethal tumor challenge and causes regression of established tumors. *Nature Med* 1995;1:471-7.
19. Chambers RS, Johnston SA. High-level generation of polyclonal antibodies by genetic immunization. *Nature Biotechnol* 2003;21:1088-92.
20. Aslakson CJ, Miller FR. Selective events in the metastatic process defined by analysis of the sequential dissemination of subpopulations of a mouse mammary tumor. *Cancer Res* 1992;152:99.
21. Pease DC. Histological techniques for electron microscopy. New York and London: Academic Press; 1964.
22. Stenberg PE, Shuman MA, Levine SP, Bainton DF. Redistribution of α -granules and their contents in thrombin-stimulated platelets. *J Biol Chem* 1984;98: 748-60.
23. Lancellotti M, Brocchi M, da Silveira WD. Bacteria-induced apoptosis: an approach to bacterial pathogenesis. *Braz J Morphol Sci* 2006;23:75-86.
24. North BM. Murine Listeriosis as a model of antimicrobial defense. *Immunol Rev* 1997;158:27-36.
25. Rogers HW, Unanue ER. Neutrophils are involved in acute, nonspecific resistance to *Listeria monocytogenes* in mice. *Infect Immun* 1993;61:5090-6.
26. Unanue ER. Inter-relationships among macrophages, natural killer cells, and neutrophils in early stages of *Listeria* resistance. *Curr Opin Immunol* 1997;1:25-43.
27. Wadsworth S, Goldfine H. Mobilization of proteinase C in macrophages induced by *Listeria monocytogenes* affects its internalization and escape from the phagosome. *Infect Immun* 2002;70:4650-60.
28. Schnupf P, Portnoy DA, Decatur AL. Phosphorylation, ubiquitination and degradation of Lysteriolysin O in mammalian cells: role of the PEST-like sequence. *Cell Microbiol* 2006;8:353-64.
29. Abelman HW. In: *Cancer as I see it*. New York: Philosophical Library, Inc.; 1951.
30. Yu YA, Shabahang S, Timiryasova TM, et al. Visualization of tumors and metastases in live animals with bacteria and vaccinia virus encoding light-emitting proteins. *Nature Biotechnol* 2004;22:313-20.
31. Stritzker J, Pilgrim S, Szalay AA, Goebel W. Prodrug converting enzyme gene delivery by *L. monocytogenes*. *BMC Cancer* 2008. doi: 10.1186/1471-2407-8-94.
32. Gajewski TF, Meng Y, Harlin H. Immune suppression in tumor microenvironment. *J Immunother* 2006;29: 233-40.
33. Rothman J. The first use of Live *Listeria* cancer vaccine in man. Abstract 225. AACR Conference, San Diego, CA. April 12-16, 2008.