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*J Immunol* published online 30 April 2010
http://www.jimmunol.org/content/early/2010/04/30/jimmunol.0901215

Supplementary Material
http://www.jimmunol.org/content/suppl/2010/04/30/jimmunol.0901215
5.DC1

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Rat (r)Erbb2 transgenic BALB-neuT mice genetically predestined to develop multiple invasive carcinomas allow an assessment of the potential of a vaccine against the stages of cancer progression. Because of rErbb2 expression in the thymus and its overexpression in the mammary gland, CD8+ T cell clones reacting at high avidity with dominant rErbb2 epitopes are deleted in these mice. In BALB-neuT mice with diffuse and invasive in situ lesions and almost palpable carcinomas, a temporary regulatory T cells depletion combined with anti-rErbb2 vaccine markedly enhanced the anti-rErbb2 Ab response and allowed the expansion of latent pools of low-avidity CD8+ T cells bearing TCRs repertoire reacting with the rErbb2 dominant peptide. This combination of a higher Ab response and activation of a low-avidity cytotoxic response persistently blocked tumor progression at stages in which the vaccine alone was ineffective. However, when diffuse and invasive microscopic cancers become almost palpable, this combination was no longer able to secure a significant extension of mice survival. *The Journal of Immunology*, 2010, 184: 000–000.

The consistent stepwise progression of tumors arising in tumor-prone genetically engineered mice allows the assessment of the ability of a vaccine to both provide protection against progressive stages of neoplasia and to elicit a response from an immune system negatively imprinted by the slow expansion of an autochthonous tumor. In these cancer models, vaccination can significantly prevent neoplastic progression for nearly as long as a mouse’s natural life span but is usually unable to cure advanced microscopic lesions (1).

This loss of efficacy is due to a tumor’s increasing ability to augment its mitotic activity, clonal diversification, and inaccessibility to the mechanisms of the immune reaction. However, the efficacy of a vaccine administered to mice bearing diffuse microscopic lesions is also diminished by the tumor-driven expansion of various kinds of negative regulatory cells (1). Numerous experiments show that this expansion results in both a far less significant immune response and suppression of its effector arm (2–9).

Tumor-driven regulatory cells expansion also changes the tumor-specific T cell repertoire (5, 10) as a result of both direct contacts and the production of soluble factors such as TGF-β or IL-10. In a special way, regulatory T (T<sub>reg</sub>) cells may inhibit the reaction of low-avidity T cells against tumor Ags (10).

This study assesses the significance of T<sub>reg</sub> cell expansion in the inefficacy of vaccination against different stages of tumor progression in female BALB/c mice transgenic for the transforming rat (r)Erbb2/neu (tErbb2) oncogene (BALB-neuT mice) (11) that develop invasive and metastatic mammary cancer (12). We have previously shown that expression of the rErbb2 protein product (Erbb2) in their thymus and mammary glands has a dramatic impact on the repertoire of CD8+ T cells that reach the periphery. By contrast with wild-type BALB/c mice, anti-rErbb2 immunization does not elicit a detectable cytotoxic response in BALB-neuT mice (13, 14). Because they are devoid of the CD8+ T cell clones that react in the wild-type with high avidity against the immunodominant rErbb2 peptide (15), their antitumor reactivity is mostly confined to CD4+ T cells and Ab production (15–17).

Hyperplastic foci appear from the 4th wk of age in all mammary glands of BALB-neuT mice, expand to multiple areas of atypical hyperplasia and give rise to disseminated tumor cells and micrometastasis in bone marrow and lungs (10th wk), and progress to in situ carcinomas (14th wk), which expand and merge to give rise to carcinomas that are initially microscopic (16th wk), then become diffuse and invasive (18th wk) and almost palpable around the 20th wk (12, 18). This progression is accompanied by rampant immune suppression. Expansion of T<sub>reg</sub> cells (19) and immature myeloid cells (20) along with NKT cells (21) progressively inhibits natural
immune surveillance. We have shown that chronic infusion of anti-CD25 Ig results in a sustained depletion of T<sub>reg</sub> cells, greatly delays carcinogenesis, and unveils a natural immune response to rErbb2 (19).

In this study, we set out to determine whether anti-rErbb2 DNA vaccination combined with temporary T<sub>reg</sub> cell depletion provides better protection against stages of mammary lesions whose progression can no longer be inhibited by vaccination alone. In BALB-neuT mice harboring microscopic in situ lesions and most palpable carcinomas, this combination markedly enhanced the anti-rErbb2 Ab response and allowed both the expansion of latent pools of low-avidity CD8<sup>+</sup> T cells bearing TCR repertoire reacting with the rErbb2 dominant peptide and their activation against this peptide. The result was a persistent blockade of tumor progression at stages in which the vaccine alone was ineffective, whereas survival of mice with diffuse, invasive, and almost palpable microscopic lesions was not significantly extended.

Materials and Methods

Mice

SCID mice, wild-type BALB/c mice, and BALB-neuT 6-wk-old female mice were from Charles River Laboratories Italia (Calco, Italy). BALB-neuT mice overexpress the rErbb2 transforming oncogene under the control of the mouse mammary tumor virus promoter and develop a multifocal and metastatic carcinoma in each of their 10 mammary glands with a stepwise progression (12,18). BALB-neuT mice unable to produce Abs (BALB-neuT/BKO mice) were generated by crossing BALB-neuT mice with BALB/c mice knocked out for the Ig<sub>κ</sub> chain (BALB-neuT/BKO mice) were generated by crossing BALB-neuT mice with BALB/c mice knocked out for the Ig<sub>κ</sub> chain (17). Mice were randomly assigned to control and treatment groups, and all groups were treated concurrently. Mammary glands were inspected weekly to note tumor appearance. Neoplastic masses were then measured with calipers in two perpendicular diameters, and the average value was recorded. Progressively growing masses >1 mm mean diameter were regarded as tumors. Tumor volume was calculated as (X<sup>2</sup> X Y)/2, where X and Y represent the short and long diameters, respectively. Total tumor volume is the sum of individual tumor volumes of each mouse and is reported as mean ± SD. Tumor multiplicity was calculated as the cumulative number of incident tumors/total number of mice at the time of death. Values are reported as mean ± SEM. Mammary whole-mount preparations were performed as reported previously (19). According to our ethical protocol, mice were killed when a first tumor exceeded 10 mm mean diameter. All the experiments were approved by the institutional ethical committee, and mice were treated in accordance to the European Union guidelines.

Production and administration of anti-CD25 Ig

The PC61 hybridoma-secreting IgG1 mAb to the α-chain of murine IL-2R (CD25) was purchased from the American Type Culture Collection (Manassas, VA) and cultured in DME (Sigma-Aldrich, St. Louis, MO) supplemented with 5% FBS (Life Technologies, Carlsbad, CA). These cells were cultured in DMEM supplemented with 20% FBS at 37˚C in a humidified 5% CO<sub>2</sub> atmosphere. FITC-conjugated goat anti-mouse Abs specific for mouse IgG Fc (Fc) were used to detect bound primary Abs. Normal mouse serum was used as negative control. The mAb Ab4 (OncoGene Research Products, Cambridge, MA), which recognizes an extracellular domain of rErbb2, was used as a positive control. After washing, cells were suspended in PBS-azide-BSA containing 1 mg/ml propidium iodide to exclude dead cells and evaluated in a CyAn ADP (DakoCytomation). The results are expressed as 3T3-NKB–specific binding potential calculated as follows: ([% positive cells with test serum] [fluorescence mean]) – ([% positive cells with control serum] [fluorescence mean]) X serum dilution as previously described in detail (24).

Cytotoxic T lymphocyte assays

To prepare target cells for in vivo cytotoxicity detection (25), erythrocytes in BALB/c spleen cell suspension (SPC) were removed by osmotic lysis. Cells were then washed and split into two target populations. One was labeled with 5 μM CFSE (Molecular Probes Invitrogen, Carlsbad, CA), then pulsed with the dominant 63–71 rErbb2 peptide (p63–71, TVYPVANSL; INBIOS Srl, Naples, Italy) with H-2K<sup>d</sup> restriction element (26) at a concentration of 3 or 15 μg/ml for 1 h at 37°C (CFSE<sup>low</sup> cells). For injection, an equal number of SPCs from each population were mixed together. Recipient mice were injected i.v. with 20 × 10<sup>6</sup> cells suspended in 0.3 ml PBS. Mice were bled 18 h later, and PBMCs were analyzed using flow cytometry as we described previously (19). To detect IFN-γ production, lymphocytes from LNs or SPCs were cultured in presence of 3, 15, or 50 μg/ml of the p63–71 for 18 h plus 10 μg/ml brefeldin A (Sigma-Aldrich) for the last 5 h. Cells were stained with anti-mouse allophycocyanin-CD8 (BD Pharmingen) and then fixed, permeabilized, and stained simultaneously with anti-mouse IFN-γ (eBioscience).

T cell repertoire analysis

Repertoire analysis was performed as described previously in detail (15). Popliteal and inguinal LN cells were collected from the various groups of mice, and 5 × 10<sup>6</sup> cells were cultured for 3 d in the presence of 3, 15,
or 50 μg/ml p63–71 or mitomycin C (Sigma-Aldrich)-treated 3T3-NKB cells. Culture medium was RPMI 1640 medium (Life Technologies, Basel, Switzerland) supplemented with 2 mM l-glutamine, 50 μM 2-ME, 50 μg/ml gentamicin (all from Sigma-Aldrich), and 10% FBS. Total RNA was isolated from CD4+ and CD8+ immunobeads sorted cells (15) with the RNasy Mini Kit (Qiagen, Hilden, Germany), according to the manufacturer’s instructions. cDNA synthesized using an oligo-dT primer (dT15) (Invitrogen) was subjected to PCR amplification using a common Cβ primer in combination with the various Vβ primers as previously described in detail (15). Using 2 μl PCR product as a template, runoff reactions were performed with the internal fluorescent Jβ primers (15, 27). The runoff products were denatured in formamide and analyzed on an Applied Biosystems 3100 Prism using GeneScan 2.0 software (Applied Biosystems, Foster City, CA). Results are reported as rate of stimulation index (RSI = normalized peak area obtained from cells stimulated with Ag/normalized peak area of nonstimulated cells).

CD8 depletion

For CD8+ T cell depletion, BALB-neuT mice were injected with 50 μg anti-mouse CD8 mAb (Cederlane Laboratories, Hornby, Ontario, Canada) every 10 d starting the day before the first vaccination. Three weeks later, mice were challenged s.c. with 1 × 106 TUBO cells, an Erbb2+ cloned cell line established in vitro from a lobular carcinoma that arose in a female BALB-neuT mouse (13).

Statistics

Differences in data were evaluated with the two-tailed Student t test, except that differences in tumor incidence were evaluated with the Mantel-Haenszel log-rank test (11).

Results

Anti-CD25 Ig persistently impairs Treg cell expansion during rErbb2 carcinogenesis

At the 10th week of age, BALB-neuT mice display atypical hyperplasia foci scattered in all 10 mammary glands (18) and disseminated tumor cells and micrometastasis in bone marrow and lungs (12). Progression of these lesions to in situ and invasive cancer is accompanied by the expansion of CD4+CD25+GITR+FoxP3+ Treg cells (19). To examine the effect of anti-CD25 Ig on Treg cells in tumor draining LNs, 10-wk-old BALB-neuT mice received two injections of control or anti-CD25 Ig 4 d apart. Although a progressive expansion of CD4+CD25+GITR+FoxP3+ cells was evident in mice receiving control Ig, 2 wk after the injections of anti-CD25 Ig, their number fell dramatically and remained significantly lower than in control mice until about week 30 (Fig. 1).

Anti-CD25 Ig administration unveils CD8+ T cells participating in tumor halting

A marked cytotoxic response to rErbb2 following anti-CD25 Ig administration, alone or in combination with EC-TM plasmid electroporation, was a new and unexpected finding, because it had never been found in BALB-neuT mice when different protocols of immunizations were adopted (1, 13, 22, 28). Indeed, BALB-neuT mice lack the CD8+ T cells reacting with high avidity with the rErbb2 immunodominant p63–71 (15). To look for the mechanisms whereby Treg cell depletion allows anti-rErbb2 vaccination to elicit such a response, we evaluated the p63–71-specific T cell repertoire thus expanded. Wild-type BALB/c mice and BALB-neuT mice were electroporated at weeks 10 and 12 with EC-TM plasmid. A few of them, together with untreated mice, received anti-CD25 Ig 1 and 4 d after the first electroporation. At week 14, popliteal and inguinal LN cells were collected and cultured with the p63–71. The 288 Vβ-Jβ primer combinations were used to perform the first CD3R length fragment analysis on a pool of cDNA from five treated BALB-neuT mice. After in vitro restimulation with p63–71, Ag-driven perturbation of normal CD3R-β profile was observed in eight spectra from this pool (Fig. 3A). These rearrangements were then checked in other 10 (individual) mice. Three groups of rearrangements specific for the p63–71 were shared among sorted CD8+ T cells from treated mice: Vβ1-Jβ1.1 of 137 bp length (used by 4 of 10 mice), Vβ6-Jβ2.7 of 109 or 115 bp length (each used by 6 of 10 mice), and Vβ7-Jβ1.2 of 134 or 137 bp length (used by 3 of 10 and 4 of 10 mice, respectively) (Fig. 3B). Vβ9-Jβ1.2 rearrangements (98 and 104 bp length) specific for p63–71, used by the vast majority of BALB/c mice electroporated with or without anti-CD25 Ig, were never expanded in any of the BALB-neuT mice (Table I), in keeping with our previous finding (15). These data hint that the p63–71-specific repertoire expanded following Treg cell depletion in BALB-neuT mice does not overlap with that activated by EC-TM plasmid electroporation in BALB/c mice, whether alone or in combination with anti-CD25 Ig.
arrangements are also expanded in most of BALB-neuT mice receiving the EC-TM plasmid electroporation plus anti-CD25 Ig administration.

Features of p63–71-specific T cells in BALB-neuT mice

The cytotoxic response elicited in vivo by the combined treatment in BALB-neuT mice is of lower avidity than what was induced in BALB/c mice electroporated with EC-TM only. Marked cytotoxic activity in vivo is evident against target cells only when these are pulsed with 15 μM but not 3 μM p63–71 (Fig. 4A). The cytotoxic response is parallel to a sustained CD8+ T cell infiltration of mammary lesions in mice receiving the combined treatment (Fig. 4B). Accordingly, TCR repertoire analysis shows that CD8+ cells expressing the Vβ1-Jβ1.1 and Vβ7-Jβ1.2 rearrangements infiltrate tumor lesions (Fig 5B).

In vitro, too, the T cell response elicited by the combined treatment is of a relatively low avidity. Although a significant number of CD8+ T cells from EC-TM-electroporated BALB/c mice is induced to produce IFN-γ by 3 μM p63–71, 15 μM p63–71 is required to trigger CD8+ IFN-γ-secreting cells (Fig. 5A) from BALB-neuT mice receiving the combined treatment. Furthermore, the number of IFN-γ–producing T cells in these mice is also consistently lower than that in BALB/c mice (Fig. 5), even under optimal concentration of stimulating Ag. The CD8+ T cells carrying the shared rearrangements differ in their ability to expand in vitro in response to p63–71 (Fig. 5B). Those carrying the Vβ9-Jβ1.2 rearrangements used by EC-TM–electroporated BALB/c mice expand significantly already at a concentration of 3 μM p63–71; of the rearrangements used by BALB-neuT mice receiving the combined treatment, Vβ7-Jβ1.2 alone displays a marginal ability to expand in the presence of 3 μM p63–71. At the optimal concentration of 15 μM p63–71, all of the three CD8-associated rearrangements expanded but with a lower proliferative capacity than the Vβ9-Jβ1.2 cells, as indicated by the lower RSI (Fig. 5B). Though not a direct measurement, the sensitivity to Ag stimulation in vitro has been shown to reflect the Ag avidity of a T cell (29). Thus, taken together, these results suggest that the CD8+ cells activated in BALB/c mice constitute a repertoire characterized by high Ag avidity, whereas the CD8+ cells recruited in BALB-neuT mice behaves as a repertoire characterized by lower avidity.

Last, the combined treatment is still able to elicit a reaction that impairs the progression of Erbb2 lesions in BALB-neuT/BKO mice unable to produce Abs (Fig. 4C). In the same way, depletion of CD8+ cells reduces its ability to protect BALB-neuT mice from a subsequent tumor challenge (Supplemental Table II).

Anti-CD25 Ig administration expands but does not change CD4+ T cell repertoires

We have previously shown that BALB-neuT mice expand CD4+ T cells expressing the Vβ11-Jβ2.7 and the Vβ13-Jβ2.3 rearrangements following EC-TM electroporation, whereas BALB/c mice expand CD4+ cells with different TCR rearrangements (15). To determine whether EC-TM plasmid electroporation plus anti-CD25 Ig also affects the CD4+ T cell repertoire, LN cells from BALB/c and BALB-neuT mice electroporated with or without anti-CD25 Ig were cultured with rErbb2+ BALB/c 3T3-NKB cells (23). Expansion of the Vβ11-Jβ2.7 and the Vβ13-Jβ2.3 rearrangements was observed following EC-TM plasmid electroporation with or without anti-CD25 Ig administration (Table I). Administration of anti-CD25 alone led to the expansion of lymphocytes expressing the Vβ11-Jβ2.7 and the Vβ13-Jβ2.3 rearrangements in a significant number of BALB-neuT mice. These results suggest that CD4+ T cells expressing a public TCR repertoire specific for Erbb2 are naturally present in the periphery of BALB-
neuT mice and can be expanded either by active immunization or by Treg cell depletion alone. These rearrangements were not expanded in BALB/c mice receiving anti-CD25 Ig alone or in combination with EC-TM plasmid electroporation.

Anti-CD25 Ig administration enables EC-TM plasmid electroporation to cure diffuse and invasive microscopic Erbb2 carcinomas

To determine whether combination with anti-CD25 Ig improves the therapeutic efficacy of EC-TM plasmid, BALB-neuT mice received two courses of EC-TM plasmid electroporation, alone or combined with anti-CD25 Ig, at different stages of mammary cancer progression. Because Treg cells rapidly expand as a tumor grows, anti-CD25 Ig was injected 14 and 10 d before the first electroporation to remove most of them. At week 16, when multiple in situ carcinomas formed of clusters of tumor cells separated by bands of delicate stroma rich in blood vessels are scattered in all mammary glands (Supplemental Fig. 1), EC-TM plasmid electroporations alone still elicited a significant anti-rErbb2 Ab response but not a cytotoxic response, and the influence of this reaction on survival was still significant (Supplemental Fig. 1). Combination of anti-CD25 Ig led to a stronger cytotoxic response to the dominant p63–71 (Fig. 6), reduced tumor multiplicity (Supplemental Table I), and kept 36% of mice free of palpable tumors at week 100 when the experiment ended (Fig. 6).

At week 18, the clusters coalesce to form masses that invade mammary glands (Fig. 6) and are surrounded by a dense stroma with large vessels (Supplemental Fig. 1). Once again, EC-TM plasmid electroporation alone elicited a significant Ab response but not a cytotoxic response, and the influence of this reaction on survival was marginal (Supplemental Fig. 1). By contrast, the combination continued to elicit a stronger Ab and cytotoxic response and kept 33% of mice free of palpable tumors (Fig. 6) and alive (Supplemental Fig. 1) at the end of the experiment.

Discussion

BALB-neuT mice are genetically predestined to undergo one of the most aggressive metastasizing and lethal rErbb2-driven mammary carcinogenesis (11, 12). During the lengthy stepwise progression of their mammary lesions, Treg cells expand to bring about rampant immunosuppression (19). When the lesions are initial and the tumor-elicited suppression is still negligible, the protection provided by anti-rErbb2 vaccines prevents their progression and persists for almost as long as the natural life span of wild-type BALB/c mice (14, 22), whereas their efficacy dramatically fades if these initial lesions have progressed, and is almost null against diffuse invasive microscopic tumors (14, 22, 23, 30).

We now report new findings that give insight into the unveiling of latent CD8+ T cell populations, the therapeutic efficacy stemming from the combination of anti-Erbb2 DNA vaccination with anti-CD25 Ig administration, and the limit of this combined treatment in advanced microscopic tumor stages.

At week 20, larger microscopic masses start to become palpable in the mammary pad (Fig. 6). They often display central necrotic areas (Supplemental Fig. 1) because blood vessels are only present in the surrounding dense and fibrous stroma. These vessels show a diffuse NG2 and α-smooth muscle actin (markers of nascent and mature pericytes) positivity, which is absent and scarcely present in the tumor vessels of 16- and 18-wk-old mice, respectively (Supplemental Fig. 2). At this stage, EC-TM plasmid electroporation elicited only a low Ab response, whereas its combination with anti-CD25 Ig led to a slightly higher Ab response together with a substantial cytotoxic response that significantly delayed the appearance of the first palpable tumor (Fig. 6) and appreciably reduced both tumor multiplicity (Supplemental Table I) and total tumor burden (Supplemental Fig. 3), although the extension of survival was marginal (Supplemental Fig. 1).

FIGURE 3. Dominant rErbb2 peptide T cell repertoires triggered by EC-TM plasmid electroporation and anti-CD25 Ig administration in BALB-neuT mice. A, Complete CDR3-β immunoscope analysis of the immune response to p63–71 peptide in a pool of five BALB-neuT mice. Mice were electroporated on weeks 10 and 12 with EC-TM plasmid and injected with anti-CD25 Ig 1 and 4 d after the first electroporation. Their popliteal and inguinal LN cells were restimulated in vitro with the immunodominant rErbb2 peptide p63–71. cDNA were amplified by PCR with a combination of all 24 V primers and a common C primer; after a runoff reaction with 12 J fluorescent primers, products were analyzed in a DNA sequencer. ■, V-J rearrangements showing p63–71-specific expansion. B, Frequencies of the specific p63–71 peptide repertoires in 10 individual mice electroporated and treated with anti-CD25 Ig as in A. Each column shows one mouse; ■, rearrangements used by individual mice. Frequencies of usage of the rearrangements are indicated as number of mice that use that recombination per total mice.
First, in BALB-neuT mice on the threshold of mammary carcinogenesis (10 wk), two administrations of anti-CD25 Ig lead to a rapid depletion of CD4+CD25+GITR+FoxP3+ Treg cells followed by a slow return to the levels of untreated mice. This depletion alone delays the appearance of the first palpable tumor, although all mice have one or more tumors by week 27.

Second, the finding that combination of vaccination with anti-CD25 Ig triggers a significant cytotoxic response to the rErbb2 peptide in BALB/c mice (15). Treg cell depletion does not revert the clonal composition of the CD8+ TCR repertoire specific for the dominant rErbb2 peptide never achieved in BALB-neuT mice by successful immunizations with vaccines of different kinds (13, 14, 16, 22, 28, 31). Newborn BALB-neuT mice, in fact, express rErbb2 in the thymus, and central tolerance appears to delete the CD8+ T clones that interact at high avidity with the dominant H-2Kd rErbb2 peptide in BALB/c mice. Analysis of the TCR repertoire of T cells expanded following anti-rErbb2 DNA immunization showed that BALB-neuT mice lack these clones, whereas they are expanded in wild-type BALB/c mice (15).

Vβ-Jβ spectratyping shows that a low-avidity cytotoxic response is induced by vaccination plus anti-CD25 Ig; this rests on expansion of CD8+ T cells belonging to an otherwise cryptic TCR repertoire that do not expand in wild-type BALB/c. In these mice, anti-rErbb2 immunization, alone or in combination with anti-CD25 Ig, expands only high-avidity CD8+ cytotoxic T cells. These data fit in well with our previous demonstration that wild-type BALB/c and transgenic BALB-neuT mice use distinct and nonoverlapping TCR repertoires in response to rErbb2 vaccination (15).
FIGURE 6. Anti-CD25 enhances the therapeutic activity of EC-TM electroporation in BALB-neuT mice. At progressive stages of mammary carcinogenesis, BALB-neuT mice received EC-TM electroporation alone or combined with anti-CD25 Ig injected 14 and 10 d before the electroporation course. The pictures in the left panels show mammary gland whole-mount preparations performed in unvaccinated mice at 16, 18, and 20 wk of age. At 16 wk, the mammary gland displays multiple small opacities surrounding the mammary ducts indicating the presence of diffuse atypical hyperplastic lesions and several foci of in situ carcinoma. At 18 wk, several discrete dark nodules corresponding to in situ and early invasive carcinomas are present, whereas the larger nodules with irregular borders present at 20 wk are interpretable as solid invasive carcinomas. The central oval black areas are mammary LNs. Original magnification ×6.3.

<table>
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<th>Stage of mammary lesion at the first electroporation</th>
<th>Treatment</th>
<th>Titer of anti-Erbb2 antibodies (mean±SD)</th>
<th>In vivo cytotoxicity to p63+/71+ (mean and range)</th>
<th>% of tumor free mice</th>
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*whole mount images (x 0.3)
*Serum collected two weeks after the second electroporation. Titers expressed as s. b. p. x 10^3
*Cytotoxity evaluated in groups of additional three mice sacrificed two weeks after the second electroporation. Mean values of a representative experiment of three performed independently are shown.
*Incidence of tumor in BALB-neuT mice: dotted black lines, mice electroporated with empty plasmid; dotted red lines, mice injected with anti-CD25; black lines, mice electroporated with EC-TM only; red lines, mice receiving both treatment. Statistical analysis of survival: red asterisks, mice electroporated with EC-TM only versus those receiving EC-TM only, black asterisks, mice electroporated with EC-TM only versus those receiving the empty plasmid. **p<0.0001, ***p<0.001, *p<0.05.
is effective. In mice bearing an atypical hyperplasia in all mammary glands, our anti-ErbB2 DNA vaccine alone doubles the survival time, but by the 65th week of age, all mice have developed tumors. Moreover, although the efficacy of the DNA vaccine alone is no more than marginal in mice bearing diffuse in situ carcinoma (16th week of age) and early microscopic invasive cancer (week 18), its combination with anti-CD25 Ig was still able to keep a significant number of mice tumor free at week 100, whereas in those that developed tumors, tumor multiplicity was significantly reduced. This is probably the most significant finding of this study. Fourth, even the more composite and effective immune response induced by the combination of anti-ErbB2 vaccination with anti-CD25 Ig loses most of its efficacy as the microscopic lesions progress. Survival, in fact, is no more than marginally extended if this combination is administered when they are nearly palpable in the mammary pad (20th wk of age), because it does no more than slow down the progress of a few lesions and reduce the number of tumors per mouse. This loss of efficacy is probably due to increased resistance acquired by the more advanced neoplastic lesions as they become more compact and refractory to the immune mechanisms thus activated (43, 44). The growth of these lesions is fatal, even if the expansion of smaller lesions is still controlled by the immune response. However, our data also point to a marked decrease of the intensity of the immune response elicited by the combination in mice bearing invasive microscopic cancer. Although anti-CD25 Ig still results in Treg cell deletion (data not shown), this interference with negative regulatory cells is no longer decisive when assessing the significance of vaccination plus Treg cell deletion in a clinical setting, because it is quite possible that the different patterns and timing of transgene expression lead to an immune tolerance to Erbb2 different from that of tumor patients (1).

Acknowledgments
We thank Prof. John Iliffe (Turin, Italy) for editing the manuscript.

Disclosures
The authors have no financial conflicts of interest.

References
J. A. Berzofsky. 2005. Early role of CD4+ Th1 cells and antibodies in HER-2
adenovirus vaccine protection against autochthonous mammary carcinomas. J.
29. Fassò, M., N. Anandadasapathy, F. Crawford, J. Kappler, C. G. Fathman,
and W. M. Ridgway. 2000. T cell receptor (TCR)-mediated repertoire selection
and loss of TCR Vβ diversity during the initiation of a CD4+ T cell response in vivo.
30. Curcio, C., A. S. Khan, A. Amici, M. Spadaro, E. Quaglino, F. Cavallo, G. Forni,
and R. Draglia-Akli. 2008. DNA immunization using constant-current electro-
poration affords long-term protection from autochthonous mammary carcinomas
31. Sakai, Y., B. J. Morrison, J. D. Burke, J. M. Park, M. Terabe, J. E. Janak, G. Forni,
J. A. Berzofsky, and J. C. Morris. 2004. Vaccination by genetically modified den-
dritic cells expressing a truncated neu oncogene prevents development of breast
32. McMahan, R. H., and J. E. Slansky. 2007. Mobilizing the low-avidity T cell
33. Kedl, R. M., W. A. Rees, D. A. Hilderman, B. Schaefer, T. Mitchell, J. Kappler,
and P. Marrack. 2000. T cells compete for access to antigen-bearing antigen-
34. Block, M. S., M. J. Hansen, V. P. Van Keulen, and L. R. Pease. 2003. MHC class
I gene conversion mutations alter the CD8 T cell repertoire. J. Immunol.
171: 4006–4010.
3: 9–10.
36. Jacob, J. B., Y. C. Kong, C. Meroueh, D. P. Snower, C. S. David, Y. S. Ho, and
W. Z. Wei. 2007. Control of Her-2 tumor immunity and thyroid autoimmunity by
37. Cappello, P. F. Triebel, M. Iezzi, C. Caorsi, E. Quaglino, P. L. Lollini, A. Amici,
vaccination to persistently prevent mammary carcinogenesis in HER-2/neu
39. Wing, K., Y. Onishi, P. Prieto-Martin, T. Yamaguchi, M. Miyara, Z. Fehervari,
T. Nomura, and S. Sakaguchi. 2008. CTLA-4 control over Foxp3+ regulatory
40. Lustgarten, J., A. L. Dominguez, and C. Pinilla. 2006. Identification of cross-
reactive peptides using combinatorial libraries circumvents tolerance against
41. Morgan, D. J., H. T. Keeswiel, S. Fleck, H. I. Levitsky, D. M. Pardoll, and
L. A. Sherman. 1998. Activation of low avidity CTL specific for a self epitope
42. Kim, P. S., T. D. Armstrong, H. Song, M. E. Wolpoe, V. Weiss, E. A. Manning,
ciation with HER-2/neu-targeted vaccine enhances CD8 T cell responses in mice
44. Gade, T. P., I. M. Buchanan, M. W. Motley, Mazaheri, W. M. Spees, and
15: 247–255.
45. Antony, P. A., C. A. Piccirillo, A. Akpinarli, S. E. Finkelstein, P. J. Speiss,
2005. CD8+ T cell immunity against a tumor/self-antigen is augmented by CD4+
T helper cells and hindered by naturally occurring T regulatory cells. J. Immunol.
174: 2591–2601.
Erbb2 DNA vaccine combined with T_{reg} cell deletion enhances antibody response and reveals latent low-avidity T cells. Potential and limits of its therapeutic efficacy

Supplementary Figure Legends

**Fig S1. Anti-CD25 Ig enhances the therapeutic activity or EC-TM plasmid electroporation.** At progressive stages of mammary carcinogenesis, BALB-neuT mice received two courses of EC-TM plasmid electroporations alone or associated with anti-CD25 Ig administration injected 14 and 10 days before the electroporation course. Left panels: histology of the mammary glands at the first electroporation. The histologic analysis performed at week 16 shows multiple foci of athypical hyperplasia and in situ carcinoma constituted by clusters of cancer cells separated by bands of delicate stroma (A). At 18 weeks of age the cancer cells clusters sometimes coalesce giving rise to larger and invasive neoplastic masses (C). At 20 weeks larger masses often displaying central necrotic areas are surrounded by dense and fibrous stroma (E). Magnification x 200. Right panels: percentage of survival in BALB-neuT mice injected with anti-CD25 Ig alone, grey lines; in mice electroporated with: the empty plasmid, dotted line; the EC-M plasmid alone, blue lines; the EC-TM plasmid anticipated by anti-CD25 Ig administration, red lines. Mice received the first electroporation at week 16 (B), at week 18 (D) or at week 20 (F). The statistical difference of the values in mice electroporated with EC-TM anticipated by anti CD-25 Ig versus the corresponding values in mice receiving only EC-TM electroporation, and the values in mice electroporated with EC-TM versus mice receiving the empty plasmid are reported: ***, p<0.0001; **,p<0.001; *, p<0.05

**Fig S2. Tumoral blood vessel in BALB-neuT mice.** Immunofluorescence analysis with anti-CD31 -NG2 and -αSMA. At 20 weeks of age the tumoral blood vessel wall is constituted by endothelial cells and pericytes which are scarcely present or absent at 18 and 16 weeks. Dotted yellow lines indicate the area of tumor masses. Magnification x 100.

**Fig S3. Anti-CD25 Ig effects on EC-TM plasmid electroporation performed at 20 and 22 weeks of age.** Total tumor burden in BALB-neuT mice electroporated with: the empty plasmid, dotted line; the EC-M plasmid alone, blue lines; the EC-TM plasmid anticipated by anti-CD25 Ig administration, red lines.
**Supplementary Table I: anti-CD25 Ig injection reduces tumor multiplicity**

<table>
<thead>
<tr>
<th>Group</th>
<th>Tumor number per mouse&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>9 (90/10)</td>
</tr>
<tr>
<td>10-12</td>
<td></td>
</tr>
<tr>
<td>anti-CD25 Ig</td>
<td>7.7 (77/10)</td>
</tr>
<tr>
<td>EC-TM</td>
<td>4.7 (47/10)</td>
</tr>
<tr>
<td>EC-TM + anti-CD25 Ig</td>
<td>3.6 (54/15) *</td>
</tr>
<tr>
<td>16-18</td>
<td></td>
</tr>
<tr>
<td>anti-CD25 Ig</td>
<td>7.6 (38/5)</td>
</tr>
<tr>
<td>EC-TM</td>
<td>5.2 (31/6)</td>
</tr>
<tr>
<td>EC-TM + anti-CD25 Ig</td>
<td>2.2 (24/11)**</td>
</tr>
<tr>
<td>18-20</td>
<td></td>
</tr>
<tr>
<td>anti-CD25 Ig</td>
<td>7.4 (37/5)</td>
</tr>
<tr>
<td>EC-TM</td>
<td>5.8 (47/8)</td>
</tr>
<tr>
<td>EC-TM + anti-CD25 Ig</td>
<td>1.2 (14/12)**</td>
</tr>
<tr>
<td>20-22</td>
<td></td>
</tr>
<tr>
<td>anti-CD25 Ig</td>
<td>6.3 (19/3)</td>
</tr>
<tr>
<td>EC-TM</td>
<td>7.4 (52/7)</td>
</tr>
<tr>
<td>EC-TM + anti-CD25 Ig</td>
<td>4.6 (22/8)*</td>
</tr>
</tbody>
</table>

<sup>a</sup>Cumulative number of incident tumors/total number of mice at the time of death. The statistical difference of the values in mice electroporated with EC-TM anticipated by anti CD-25 Ig versus the corresponding values in mice receiving only EC-TM electroporation were calculated by two-tailed Student’s t test and are reported: ***, p<0.0001; **, p<0.001; *, p<0.05.
Supplementary table II: CD8 depletion affects the ability of EC-TM vaccination and anti-CD25 Ig administration to protect BALB-neuT mice from a subsequent challenge of ErbB2+ tumor cells

<table>
<thead>
<tr>
<th></th>
<th>Tumor takes&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Latency&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Survival&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>5/5</td>
<td>25±3</td>
<td>54±2</td>
</tr>
<tr>
<td>EC-TM + antiCD25</td>
<td>0/5</td>
<td>&gt;60</td>
<td>&gt;60</td>
</tr>
<tr>
<td>EC-TM + antiCD25 + antiCD8&lt;sup&gt;d&lt;/sup&gt;</td>
<td>1/5</td>
<td>23</td>
<td>56</td>
</tr>
</tbody>
</table>

<sup>a</sup> number of mice with tumor out of total mice

<sup>b</sup> mean ± SD (in days) for the tumor to reach 2 mm diameter

<sup>c</sup> mean ± SD (in days) for the tumor to reach 2 mm diameter

<sup>d</sup> mice were injected every 10 days with 50 μg of anti-mouse CD8 mAb, starting one day before vaccination.