Existent T-Cell and Antibody Immunity to HER-2/neu Protein in Patients with Breast Cancer¹

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Abstract

The HER-2/neu protooncogene is amplified and overexpressed in 20–40% of invasive breast cancers. HER-2/neu protein overexpression is associated with aggressive disease and is an independent predictor of poor prognosis in several subsets of patients. The protein may also be related to cancer formation, with overexpression being detectable in 50–60% of ductal carcinomas in situ. It has been suggested that it might be possible to develop specific T-cell therapy directed against proteins involved in malignant transformation. One question is whether normal proteins that are overexpressed are appropriate targets for therapeutic immune attack. This report demonstrates that some patients with HER-2/neu-positive breast cancers have both existent CD4+ helper/inducer T-cell immunity and antibody-mediated immunity to HER-2/neu protein. Initial studies performed on 20 premenopausal breast cancer patients identified antibodies to HER-2/neu in 11 individuals. Similar antibody responses have been found in some normal individuals. The patient with the greatest antibody response was studied in detail. In addition to a humoral immune response, this patient had evidence of a significant proliferative T-cell response to the HER-2/neu protein and peptides. Similar T-cell responses have been detected in additional patients. It has been assumed that patients would be immunologically tolerant to HER-2/neu as a self-protein and that immunity might be difficult to generate. If immunity could be generated, the result might be destructive autoimmunity. The current data support the notion that HER-2/neu-specific immunity might be used in therapy without destroying normal tissue but also raises questions as to the role of existent immunity in immune surveillance and cancer progression.

Introduction

The HER-2/neu protooncogene encodes a receptor-like transmembrane protein with a relative molecular mass of 185 kDa (p185) and homology to epidermal growth factor receptor (1). The function of HER-2/neu protein is not well defined but is associated with increased tyrosine kinase activity (2). Several ligands have been proposed for HER-2/neu (3, 4) which can induce either stimulatory or inhibitory signals, depending upon ligand and/or experimental conditions (3, 5). In the rat, the protooncogene is activated by a transforming point mutation in the transmembrane domain (1). In human breast cancer no point mutations have been found (6), and the transforming activity is thought to be related to overexpression of protein with normal structure. Overexpression of the HER-2/neu protein has been identified in many human cancers, largely adenocarcinomas of breast, ovary, colon, and lung, and is linked with poor prognosis in subsets of patients with breast cancer (7). HER-2/neu protein is selectively overexpressed by malignant cells and thus has been considered as a possible target for T-cell and antibody-mediated immunotherapy (8). HER-2/neu protein is expressed during fetal development. In adults it is detectable in small amounts in a limited number of normal tissues (9). The assumption has been that any immune response might be selective and have minimal toxicity on normal tissues expressing basal levels of HER-2/neu protein. An alternative view is that normal individuals would be tolerant to HER-2/neu as a self-protein and that if tolerance were circumvented by therapy the result might be autoimmunity directed against HER-2/neu-positive normal tissues. As preliminary studies to the development of HER-2/neu-specific immunotherapy, the current studies were initiated to evaluate whether base-line immunity to HER-2/neu existed in patients with breast cancer. Several patients were found in initial studies to have antibody responses to HER-2/neu protein. The one patient with the highest antibody response reported herein was studied in detail and was determined to have both existent antibody and T-cell immunity to the overexpressed oncogenic protein. A more extensive evaluation of patients and normals is required to determine the frequency with which immunity occurs and to determine the extent to which immunity correlates with disease parameters.

Materials and Methods

Patient History. The patient is a 63-year-old female who was first diagnosed with breast cancer in 1988. She had a family history of breast cancer, with both her sister and daughter diagnosed with the disease. At the time of mastectomy she was found to have a 4 x 4 x 3.5-cm left breast mass that was 80% high grade infiltrating ductal carcinoma and 20% intraductal carcinoma. Immunocytochemistry revealed an estrogen receptor level of 5 pmol and non-detectable progesterone receptor. The HER-2/neu protein was positive. Three of 10 axillary lymph nodes were positive for metastatic disease. She was treated with 50 Gy to the affected breast and axilla and received adjuvant chemotherapy of cyclophosphamide, 5-fluorouracil, and methotrexate for 6 months after surgery. After the end of that therapy, she was placed on p.o. tamoxifen. There was no evidence of disease until April 1992 when an abnormal mammogram indicated abnormalities in the opposite breast. Biopsy revealed a 1.2 x 0.6 x 0.5-cm infiltrating ductal carcinoma with a 20% component of ductal carcinoma in situ with comedo features. Immunocytochemistry showed an estrogen receptor/progesterone receptor-negative HER-2/neu protein-positive tumor. Due to other medical reasons, the patient underwent biopsy alone followed by local radiation therapy to the area of tumor. Now, 1 year from the development of her most recent cancer, she has no evidence of local or systemic disease.

Human Sera and Lymphocytes. Sera and lymphocytes were obtained with informed consent. The sera were stored at −20°C prior to testing. PBMC were isolated from heparinized peripheral blood by Ficoll/Hypaque density gradient centrifugation. Cells were washed, aliquoted to concentrations of 2 x 10⁷ PBMC, and resuspended in RPMI 1640 (Gibco, Grand Island, NY) with 2.5 x 10⁻⁵ M 2-mercaptoethanol, 200 units/ml penicillin, 200 units/ml strep-

¹ The abbreviations used are: PBMC, peripheral blood mononuclear cells; MHC, major histocompatibility complex; ICD, intracellular domain; SI, stimulation index; ECL, enhanced chemoluminescence.
tomycin, 10 mM L-glutamine, and 10% fetal calf serum; 10% dimethyl sulfoxide was added. The cells were then cryopreserved. Sera and lymphocytes were also obtained from normal donors after informed consent. They were processed in an identical fashion.

**Synthetic Peptides.** Three peptides were constructed, derived from the amino acid sequence of the HER-2/neu protein. The peptides, 15 amino acids in length, were chosen based on an increased probability of binding to Class II MHC molecules. This theoretical potential was evaluated by the use of a protein sequence analysis package, TSiT, that incorporates several computer algorithms designed to distinguish potential sites for T-cell recognition (10).

Two searching algorithms were used: (a) the AMPHI algorithm described by Margalit (10, 11) identified epitope motifs according to α helical periodicity and amphipathicity; (b) the Rothbard and Taylor algorithm identified epitope motifs according to charge and polarity patterns (12). Using this analysis, we identified more than 40 potential T-cell epitopes in the HER-2/neu protein corresponding to the AMPHI and the Rothbard motifs that would have the potential for binding to Class II MHC molecules. From this group, three peptides were chosen for synthesis, p42-56 (HLDMLRHLYQGCQVV), corresponding to the AMPHI and the Rothbard motifs that would have identified more than 40 potential T-cell epitopes in the HER-2/neu protein. The peptides, 15 amino acids in length, were chosen based on an increased probability of binding to Class II MHC molecules. The peptides were synthesized and purified by Dr. P. S. H. Chou (University of Washington, Seattle, WA), then dissolved in phosphate-buffered saline (pH 7.4) to give 2 mg/ml stock solutions. Prior to aliquoting they were sterile filtered, then stored at −70°C.

**p185HER-2/neu Protein.** Crudely purified p185HER-2/neu for T-cell proliferation assays as well as antibody analysis was obtained from two cell lines, either SKBR3, a human breast cancer line, or NIH 3T3 cells that had been transfected with the c-HER-2/neu DNA (13). In both cell lines, HER-2/neu is a transmembrane protein and was purified from the cell membrane fraction by modifications of described methods for other membrane-associated proteins (14). Briefly, 1 × 10^6 cells were harvested, washed, and resuspended in phosphate-buffered saline with added protease inhibitors (1 mM benzamidine, 5 μg/ml aprotinin, 1 mM phenylmethylsulfonyl fluoride). The cells were then sonicated on ice for 30 s. After documenting cellular disruption, the membrane fraction was separated from the cytosolic portion by ultracentrifugation. Presence of p185 in the membrane fraction was documented by Western blot.

**Baculovirus Construction and Purification of Intracellular Domain of HER-2/neu Receptor.** A recombinant baculovirus containing sequences encoding the ICD of the HER-2/neu receptor was constructed by using standard methods as described previously (15). Briefly, oligonucleotide polymerase chain reaction primers carrying an EcoRV restriction endonuclease site were used to amplify a DNA sequence encoding the entire intracellular domain of the HER-2/neu receptor. Following cleavage with EcoRV, the amplified DNA was cloned into the baculovirus vector pAc360. The cloning site in pAc360 was unique BamHI site which had been used by the Klenow polymerase to fill in the 5' overhangs. Following sequencing, this vector was used to construct a recombinant virus by standard methods. Recombinant HER-2/neu protein was expressed in Sf9 insect cells essentially as described previously (15). The recombinant fusion protein, which contains 11 amino acids of the baculovirus polyhedrin protein fused to the intracellular domain of the HER-2/neu protein, was purified from Sf9 cell lysates by sequential chromatography on DEAE-Sepharose, phenyl-Sepharose, and Mono Q fast protein liquid chromatography.

**Western Blot Analysis for Human Antibody Response.** Two methods of electrophoresis were used, either standard electrophoresis in a vertical apparatus, or by the Pharmacia Phast System (Pharmacia LKB Biotechnology AB, Uppsala, Sweden). p185HER-2/neu and ICD proteins were resolved on a 7.5% polyacrylamide gel in either case. After transfer to nitrocellulose (Hybond-C, Amersham) p185HER-2/neu proteins were identified by immunoblotting in an identical manner. All control blots were developed by using an IgG1 mouse monoclonal primary antibody commercially prepared, c-neu Ab3 (Oncogene Science). The primary antibody was used in a 1:1000 dilution with tris-buffered saline/1% bovine serum albumin and 0.1% Nonidet P-40. A polyclonal antiserum—horseradish peroxidase-conjugated secondary antibody (Amersham) was used in a 1:2000 dilution. After transfer to nitrocellulose (Hybond-C, Amersham) the proteins were identified by chemiluminescence reaction (Amersham ECL). Identically run experimental blots were analyzed by using the patient's sera as primary antibody. Preliminary screening studies (data not shown) demonstrated the presence of antibodies directed toward p185 derived from the SKBR3 membrane preparation in 11 of 20 selected premenopausal patients tested. The patient with the strongest antibody response to p185 was utilized for the studies to be presented below to validate existent immunity to HER-2/neu protein. Sera and lymphocytes were collected on this patient. Fig. 1 shows the Western blot of the patient serum antibody response against the p185HER-2/neu protein.

To further verify that the patient antibody responses to the 185 kD band was to p185HER-2/neu and not to possible contaminant allogeneic human proteins in the same band, the results were confirmed by using a different cell line, murine NIH 3T3, that had been transfected with human HER-2/neu complementary DNA (13). Immunoblots with control anti-HER-2/neu monoclonal antibody confirmed the presence of p185HER-2/neu protein in the membrane preparation of HER-2/neu transfected NIH 3T3 cells, but not in nontransfected wild-type NIH 3T3 cells (Fig. 2). Analysis of patient sera revealed responses to p185HER-2/neu in membrane preparations of the transfected cells. No similar responses were detected against membrane preparations from nontransfected cells (Fig. 2).

**Antibody Responses Can Be Detected against Epitopes Located in Intracellular Domain of HER-2/neu Protein.** To partially delineate the epitopes being recognized by the HER-2/neu specific antibody, an immunoblot analysis was performed by using the patient's sera against recombinant intracellular domain protein. A strong response was detected (Fig. 3).

**A Proliferative T-Cell Response Was Detected toward Both Intracellular and Extracellular Domain Peptides.** In general, immunoglobulin class switching occurs in the presence of cognate T-cell help. The detection of IgG responses to HER-2/neu protein provided inferential evidence for the possible coexistence of helper T-cells recognizing cognate epitopes on the same protein. Helper T-cell responses to p185HER-2/neu protein and to selected potential immunodominant epitopes were evaluated with standard proliferation assays. Potential immunodominant epitopes for CD4+ helper T-cell responses were chosen by use of computer algorithms, as described in "Materials and Methods." Peripheral blood lymphocytes from the patient were tested in a proliferation assay for stimulation with partially purified p185HER-2/neu protein, the HER-2/neu peptides p42-56, 82-96, and p185HER-2/neu protein, the HER-2/neu peptides p42-56, 82-96, and 117-131.
Fig. 1. A patient with a primary breast cancer that overexpressed HER-2/neu protein has antibodies against p185 HER-2/neu. The immunoblot in Lane B represents the reaction of the patient’s sera (1:1000 dilution) against p185 HER-2/neu purified from SKBR3 breast cancer cell line. The control strip in Lane A depicts p185 HER-2/neu developed with c-neu Ab3 antibody (Oncogene Science) as the primary antibody (1:1000 dilution). The patient has an antibody response to the HER-2/neu protein.

Fig. 2. Serum antibody response to p185 HER-2/neu protein present in membrane preparations of murine NIH 3T3 cells transfected with HER-2/neu complementary DNA. Lanes A and B show immunoblots of control murine anti-HER-2/neu antibody against transfected and nontransfected NIH 3T3 cells, validating that only the transfected cells contain human p185 HER-2/neu protein. Lanes C and D show the patient’s serum antibody response to p185 HER-2/neu protein in the transfected cell membrane preparation, but no response to the wild-type cells.

Discussion

Our evaluation of the immune response to p185 HER-2/neu oncoprotein revealed several patients with existent immunity antibody responses, one of which was studied in detail here. The HER-2/neu antibodies detected were IgG, implying that cognate helper T-cell immunity might be present and operative. T-cell immunity was evaluated in the patient with the strongest antibody response. T-cell responses in cancer patients to overexpressed oncogenic proteins have not been previously described. Human proliferative T-cell responses have been detected against mutated ras peptides (17), but these responses were elicited to mutated segments of protein uniquely present in cancer cells (i.e., putative cancer-specific antigens). The patient evaluated in the current report had a marked proliferative helper T-cell response to the protein and two immunodominant peptide epitopes were defined. The level of proliferative response detected was consistent with a primed response, raising the possibility that her tumor was able to act as a source of antigen with determinants capable of interacting with class II MHC and within the host T-cell receptor repertoire. CD4+ helper/inducer T-cell responses are normally directed to soluble antigen presented by antigen-presenting cells. It is known that the extracellular domain portion of the protein is soluble and present in the extratumor environment, therefore available for stimulation of immune T-cells (18). Existant responses were found to epitopes derived from both the extracellular (p42–56) and intracellular (p783–797) portion of the protein, indicating both segments are available to the Class II MHC antigen-processing pathway.

Antibody was detected to p185 and to the ICD. Immunity to the extracellular domain is currently being evaluated. There have been reports of antibody responses to other protooncogene-encoded proteins in cancer patients, including c-myc, c-myb, and p53 (19–21). These other oncogene proteins are normally intracellular. Antibody to intracellular proteins would not be expected to affect normal cell function. Immunogenicity could be explained by exposure of previ-
The patient had a marked response to the intracellular domain protein related to malignancy such as tumor necrosis. HER-2/neu is a trans-
vensing recombinant intracellular domain protein (described in "Materials and Methods").

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existent antibody response is in part directed against the ECD. If immunity is eradicated, however, the
time to death is more rapid. In such models, the immune T-cells that
are ineffective, or only partially effective in the primary host can be
made effective in therapy by in vitro activation and growth, and
treating the animal with increased numbers of the cultured T-cells.
Thus, HER-2/neu immunity might be augmented to provide therapeu-
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sibly lead to tumor stimulation by release of inappropriate cytokines
sites of tumor deposition. Whether anti-HER-2/neu responses are
beneficial or detrimental in patients is important to define before
augmenting that immunity in an effort to eradicate malignant cells.

Fig. 3. Antibody responses can be detected against epitopes located in the intracellular domains. Sera from the patient described were used as primary antibody in an immunoblot using recombinant intracellular domain protein (described in "Materials and Methods"). The patient had a marked response to the intracellular domain protein.

ously sequestered proteins to the immune system by mechanisms related to malignancy such as tumor necrosis. HER-2/neu is a trans-
membrane growth factor receptor. Antibody to the extracellular do-
main might profoundly alter cell function by stimulating the receptor
or by blocking the function of the normal ligand(s). As examples,
heterologous antibodies against HER-2/neu have been shown to pro-
vide either agonistic or antagonistic effects dependent upon the par-
ticular antibody (22). Natural ligands for HER-2/neu have been re-
ported to have variable effects depending upon the concentration (4,
5). Since helper T-cell immunity was detected and since antibody
tolerance to self-proteins in some circumstances is due to helper T-cell
tolerance and not deletion of self-reactive B-cells, it is possible that
the existing antibody response is in part directed against the ECD.

Of critical importance is the role of detected T-cell immunity in
tumor progression. In animal models, immune T-cells often coexist
with progressive fatal tumors, and the animal will die of disease
despite existent immunity. If immunity is eradicated, however, the
time to death is more rapid. In such models, the immune T-cells that
are ineffective, or only partially effective in the primary host can be
made effective in therapy by in vitro activation and growth, and
treating the animal with increased numbers of the cultured T-cells.
Thus, HER-2/neu immunity might be augmented to provide therapeu-
tic benefit. Alternatively, immunity to HER-2/neu protein could pos-
sibly lead to tumor stimulation by release of inappropriate cytokines
sites of tumor deposition. Whether anti-HER-2/neu responses are
beneficial or detrimental in patients is important to define before
augmenting that immunity in an effort to eradicate malignant cells.

Tumor immunosurveillance is a much debated concept, in part,
because few antigen systems are available to confirm or deny any
hypothesis. The presence of immunity to the HER-2/neu protein in
patients with breast cancer now provides that system. Although HER-
2/neu protein overexpression is associated with 20–40% of frank
breast carcinomas, it is found in 50–60% of ductal carcinoma in situ
(23). The decrease in HER-2/neu-positive cells in invasive ductal
carcinomas may possibly be due to immune surveillance. If that
hypothesis is correct, then T-cells in some patients who have HER-
2/neu positive ductal carcinoma in situ may be able to totally eradicate
malignant cells and prevent the development of invasive carcinomas,
whereas T-cell immunity in other circumstances might select for HER-
2/neu-negative cancer cells. HER-2/neu-positive invasive cancers that
are able to progress in the presence of immunity would presumably be
biologically the most aggressive.

The current report focused on the elucidation of the immune re-
sponse in a single patient with a high antibody response. We have
detected antibody responses to the p185HER-2/neu protein in other
patients, as well as in some normal individuals, but they have not yet
been studied in detail. Correlation of response in large numbers of
patients with protein overexpression, stage, and histology of the pri-
mary breast cancer, and clinical outcome must be determined. Large
numbers of age-matched nonaffected individuals need to be studied as
well. If the concept of immunosurveillance is valid, the detection of
immune responses might be used as a tool for early diagnosis or
screening. This would be the case if antibody response level or epit-
opettes recognized prove to be preferential for patients with malignancy
and develop early in the course of the disease, before the tumor is
otherwise manifest or large enough for detection by conventional
methods. The detection of antibody in several normal individuals
would at this point mitigate against that hypothesis, but delineation
will require analysis of a large population of normal individuals to
determine the false-positive frequency. Whether or not immunity is
predictive of malignancy, levels of existent immunity may change in
a predictable fashion in response to changes in clinical circumstances,
such as the recurrence of a HER-2/neu-positive malignancy and aid in the assessment of clinical status.

Development of successful strategies for immunotherapy of human cancers has been an area of intense investigation of several years. While encouraging results have been reported for nonspecific therapies, specific cures for individual malignancies are not yet uniformly available. This demonstration that a patient with a HER-2/neu-positive breast cancer has an immune response toward the HER-2/neu protein supports the concept that oncogenic proteins might serve as tumor antigens in human malignancy. Furthermore, definition of the immunodominant epitopes will aid in identifying potential determinants for use in T-cell vaccines or T-cell-mediated immunotherapy. Since some patients are not tolerant to this overexpressed self-protein, elicitation of immune responses in nonimmune cancer-bearing individuals should be expected. Detection of immunity without any evidence of autoimmune destruction of normal tissue provides some comfort that therapies centered on augmenting T-cell immunity will not induce toxic autoimmunity in humans. HER-2/neu protein overexpression in breast cancer is linked with a younger population, the premenopausal patient, and more aggressive disease. This is the patient population with the highest morbidity and mortality associated with their breast cancers. The results described here should help stimulate investigation into the use of the HER-2/neu oncoprotein as a target for specific immunotherapy of breast cancer.

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The ability of patients to mount an immune response against the HER-2/neu protein is further supported by the finding that tumor-associated cytotoxic T-lymphocyte expanded from a patient with ovarian cancer was found to respond to HER-2/neu peptides (24).

References

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