Targeting Tomoregulin for Radioimmunotherapy of Prostate Cancer

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Abstract
Radiotherapy is an effective approach for the treatment of local prostate cancer. However, once prostate cancer metastasizes, radiotherapy cannot be used due to the distribution of multiple metastases to lymph nodes and bones. In contrast, radioimmunotherapy should still be efficacious in metastatic prostate cancer as radioisotopes are brought to tumor cells by targeting antibodies. Here we identify and validate a prostate-expressed molecule, tomoregulin, as a target for radioimmunotherapy of prostate cancer. Tomoregulin is a transmembrane protein selectively expressed in the brain, prostate, and prostate cancer, but not expressed in other normal tissues. Immunohistochemical studies of tomoregulin protein in clinical samples show its location in the luminal epithelium of normal prostate, benign prostatic hyperplasia, and prostatic intraepithelial neoplasia. More importantly, the tomoregulin protein is expressed in primary prostate tumors and in their lymph node and bone metastases. The nature of tomoregulin as a transmembrane protein and its tissue-specific expression make tomoregulin an attractive target for radioimmunotherapy, in which tomoregulin-specific antibodies will deliver a radioisotope to prostate tumor cells and metastases. Indeed, biodistribution studies using a prostate tumor xenograft model showed that the 111In-labeled anti-tomoregulin antibody 2H8 specifically recognizes tomoregulin protein in vivo, leading to a strong tumor-specific accumulation of the antibody. In efficacy studies, a single i.p. dose of 150 μCi (163 μg) 90Y-labeled 2H8 substantially inhibits the growth rate of established LNCaP human prostate tumor xenografts in nude mice but produces no overt toxicity despite cross-reactivity of 2H8 with mouse tomoregulin. Our data clearly validate tomoregulin as a target for radioimmunotherapy of prostate cancer. (Cancer Res 2005; 65(7): 2846-53)

Introduction
Prostate cancer continues to be the second leading cause of cancer deaths in men of the United States, with 30,000 deaths per year (see http://www.cancer.gov/docroot/STT/stt_0.asp). In the early stages of prostate cancer, tumor cells are usually localized to the prostate gland, so the organ-confined disease can be treated by surgical (radical prostatectomy) or physical (radiation therapy) means. In later stages, cancers often metastasize to the lymph nodes or bones and eventually become resistant to androgen ablation therapy (1). There is no cure for advanced metastatic androgen-independent prostate cancer.

Radiation therapy such as external beam radiation therapy or internal radiation therapy (brachytherapy) has been successfully used in the treatment of clinically localized prostate cancer because prostate cancer cells are relatively radioresistant (1). Conversely, distant metastases of prostate cancer cells escape local radiation, rendering radiation therapy useless at advanced stages of the disease. Radioimmunotherapy, in which a radiolabeled antibody specifically recognizes cancer cells, could be an appropriate treatment for metastatic prostate cancers because radiation is delivered to the metastatic cells expressing the target. Furthermore, metastatic prostate tumor cells tend to form small foci in the lymph nodes and bone marrow that are easily accessible to circulating antibodies (2).

For radioimmunotherapy, the target should be on the cell surface and abundantly and selectively expressed in disease tissues. To identify an appropriate target for radioimmunotherapy, we searched an expression database and found tomoregulin to be expressed on prostate and prostate cancer cells. In this study we verify the expression of tomoregulin on prostate cancer cells and show that tomoregulin is recognized by the specific antibody 2H8 in vivo, and that the administration of 90Y-labeled 2H8 inhibits the growth of tumor xenografts (LNCaP) in nude mice.

Materials and Methods

Cell culture. The human prostate carcinoma cell lines LNCaP, PC-3, and DU 145 were obtained from American Type Culture Collection (Manassas, VA) and grown in RPMI 1640, supplemented with 10% fetal bovine serum (FBS) and penicillin/streptomycin at 37°C in a humidified atmosphere of 5% CO2 (3, 4). The Clone36 cell line was generated by stably transfecting PC-3 cells with the expression vector pcDNA3.1-tomoregulin. These cells were maintained in RPMI 1640, supplemented with 10% FBS and 400 μg/ml G418.

Northern blot analysis. Northern blot analysis was done as previously described (5). Total RNA was isolated using the RNaseasy kit (Qiagen, Valencia, CA) from cultured LNCaP, PC-3, DU 145, and PrEC cells according to the instructions of the vendor. Twelve-microgram samples of total RNA were denatured on a 1% denatured agarose gel and fractionated by electrophoresis and transferred to Hybond-N+ nylon membrane (Amersham, Piscataway, NJ). The bound RNA was immobilized by UV cross-linking and then hybridized with a random-primed 32P-labeled tomoregulin probe at 70°C. To control for RNA sample loading and transfer efficiency, blots were also hybridized at 68°C with a 32P-labeled human cDNA for actin.

Quantitative real-time reverse transcription-PCR. Expression of tomoregulin was measured by TaqMan assay using FAM dye on cDNA reversed transcribed from total RNAs. PCR reactions were carried out using an ABI Prism 7700 Sequencing Detection system (Perkin-Elmer Applied Biosystems, Foster City, CA). Glyceraldehyde-3-phosphate dehydrogenase (GAPDH) expression as normalizer was measured using the Perkin-Elmer GAPDH kit.

Recombinant protein production. The extracellular domain of tomoregulin comprising amino acids 1 to 302 was expressed as a secretory protein in the baculovirus expression system. Briefly, the cDNA

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encoding the extracellular domain was amplified with primers encoding for an N-terminal optimized Kozak sequence and a C-terminal 6-His tag which is preceded by two glycine residues and followed by a stop codon. The PCR product was restricted with the enzymes BamHI and KpnI and cloned downstream of the polyhedrin promoter into the baculovirus transfer vector pHBS290. Recombinant baculovirus was produced by cotransfection with BaculoGold DNA (BD Biosciences, Palo Alto, CA) and subsequent plaque isolation. High Five cells were infected at a multiplicity of infection of 3 and the cell culture supernatant was harvested after 72 hours. The protein was purified in a two-step procedure by Ni²⁺-chelating and size exclusion chromatography.

**2H8 antibody.** 2H8 antibody is a murine IgG1 monoclonal antibody that reacts with the follistatin domains of the extracellular region of tomoregulin protein. The antibody was recently described (6). A nonspecific control antibody, mouse IgG1, was purchased from BD Biosciences (Palo Alto, CA).

**Western blot analysis.** Whole cell lysates in radioimmunoprecipitation assay buffer [150 mmol/L NaCl, 10 mmol/L Tris pH 7.2, 0.1% SDS, 1% Triton X-100, 1% deoxycholate, 5 mmol/L EDTA, protease inhibitors cocktail tablet (Roche Molecular Biochemicals, Mannheim, Germany)] containing 25 to 100 µg of protein were separated by 10% SDS-PAGE under nonreducing condition and transferred to nitrocellulose membrane. The blots were probed with 2H8 against tomoregulin and peroxidase-conjugated goat anti-mouse IgG antibody (Pierce, Rockford, IL) as secondary antibody. The signal was detected using the enhanced chemiluminescence detection system (Amersham).

**Generation of antibody-chelator conjugates.** All equipment used was rendered metal-free with 10 mmol/L EDTA followed by extensive rinsing with Chelex-treated MilliQ water. Buffers were prepared with reagents containing minimal trace metals and were treated with Chelex resin (Bio-Rad, Hercules, CA) to remove residual metals. Antibodies were concentrated to ~5 mg/mL by ultrafiltration and EDTA was added to 1 mmol/L and incubated for 1 hour to remove bound trace metals. Buffer exchange into 50 mmol/L sodium bicarbonate, 150 mmol/L NaCl, pH 8.5, was done using a G25 column (Pharmacia Desalt 26/10). Antibody-containing fractions were concentrated to 5 to 10 mg/mL. A stock solution of p-SCN-benzyl-DTPA was prepared in DMSO (100 mg/mL) and added to the antibody solution to a molar ratio of 50:1 (DTPA/antibody). The conjugation reaction was run overnight at room temperature. The reaction mixture was run on a G25 column to remove unreacted DTPA and to exchange buffer to 50 mmol/L sodium acetate, 150 mmol/L NaCl, pH 6.5. Total protein concentration of the final immunoconjugate was determined by bichromonic acid (BCA) assay (Pierce) and the antigen-binding activities of the immunoconjugates were determined by ELISA.

**Radiolabeling of antibody-chelator conjugates.** Radiolabeling of the antibody-chelator conjugates with ¹¹¹In or ⁹⁰Y was done via chelation of the radiometal to the DTPA moiety of the conjugate. Radioisotopes (Perkin-Elmer Lifesciences, Inc, Boston, MA) were first buffered by adding an equal volume of 100 mmol/L NH₄OAc (pH 5.5), then antibody-conjugate was added to a ratio of 1 mg antibody/mCi. The reaction was incubated for 1 hour, with mixing at room temperature, then EDTA was added to a final concentration of 1 mmol/L, to scavenge nonspecifically bound radioisotope for 15 minutes at room temperature. Radiolabeled antibody was separated from free radioisotope, and buffer exchanged into PBS, using a Pharmacia 26/10 Desalting column run at 2 mL/min, while collecting 1-mL fractions. Peak fractions were collected and sodium ascorbate was added at 1.0 mg/mL for ⁹⁰Y-labeled antibodies to serve as radioprotectant.

Activity of the ⁹⁰Y-radioconjugates was measured by liquid scintillation counting, and a γ-counter was used for the ¹¹¹In-conjugates. Total protein concentration was determined using BCA assay (Pierce), and specific activities were calculated based on these results. Levels of free radioisotope and free DTPA were determined by TLC using a previously published method (7). The antigen binding activity of the radioconjugate was measured by ELISA or by radioimmunounassay. Typically, specific activities ranged from 0.25 to 1.0 mCi/mg. TLC results indicated that free ¹¹¹In and free DTPA levels were generally less than 3% and frequently less than 1% of the total activity. The DTPA conjugation and radiolabeling procedure did not affect immunoreactivity (by ELISA) of 2H8.

**Results**

**Tomoregulin mRNA is selectively expressed in the brain, prostate, and prostate cancer.** A bioinformatics approach was used to search a commercial gene expression database (Incyte, Palo Alto, CA) for genes that are expressed in prostate/prostate cancer but not in essential normal tissues. One of the genes identified encodes tomoregulin (6, 8–10), which was expressed in only two tissue categories (male genitalia and nervous system; Table 1). Tomoregulin mRNA was found in 19 cDNA libraries derived from male genitalia. Eighteen of these libraries were generated from prostate tissues, of which 10 were derived from prostate tumors (data not shown). Importantly, tomoregulin expression was not detected in any of the 159 cDNA libraries generated from cells of the immune and immune system (Table 1).

The predicted predominant species of tomoregulin mRNA is 2.2 kb (6), encoding a protein of 334 amino acids with a calculated molecular weight of about 37,000 to 51,000 (6). Based on our homology analysis, tomoregulin is predicted to have a single transmembrane domain, two follistatin modules, and one epidermal growth factor (EGF)-like domain (data not shown).
Tomoregulin mRNA was detected in normal prostate and benign prostatic hyperplasia as well as in prostate tumor (Fig. 1). Moreover, expression levels of tomoregulin mRNA in these prostate specimens were much higher than those in the LNCaP human prostate cancer cell line.

**Tomoregulin protein is detected in clinical samples of prostate tumors and prostate tumor metastases.** Expression of tomoregulin protein in human tissues was determined by immunohistochemistry using the anti-tomoregulin mouse monoclonal antibody 2H8 (6). 2H8 binds specifically to human tomoregulin protein with high affinity ($K_D = 1.24 \text{ nmol/L}$), as determined by BIACore analysis (data not shown). It does not bind to its close homologue tomoregulin-1 or TMEFF-1 protein (ref. 8; data not shown).

To verify the tissue-specific expression of tomoregulin, 11 human normal tissues including prostate, brain, heart, lung, liver, pancreas, small intestine, kidney, spleen, skeletal muscle, and skin were evaluated by immunohistochemistry using 2H8. Mab2H8 was highly reactive with biopsies from normal prostate and produced intense staining in the glandular lumen. Specifically, the positive staining was distributed in the prostate luminal epithelial cells, but not in the basal cells. Some moderate staining was also seen in the brain (Fig. 2). In contrast, all of the other human tissues tested were negative for tomoregulin protein expression.

Expression of tomoregulin protein was also determined by immunohistochemistry using tumor tissue samples from prostate cancer patients. Overall, tomoregulin protein was strongly expressed in prostate primary tumors and their metastatic tissues. Intense positive staining was detected in prostate tumor tissues as well as in prostatic intraepithelial neoplasia, the precursor lesion of prostate carcinoma (Fig. 2). Adjacent normal tissues also showed some staining. Most importantly, tumor cells of the metastatic lesions in lymph node and bone showed very strong positive staining using anti-tomoregulin antibody 2H8 (Fig. 2). Therefore, the tomoregulin protein is highly expressed in both normal prostate and prostate tumor tissues, and it is also highly expressed in late-stage prostate carcinoma including metastatic tissues from lymph node and bone.

**Expression of tomoregulin mRNA and protein in the LNCaP prostate cancer cell line model.** We also investigated the expression of tomoregulin in cultured prostate cells to identify appropriate models for *in vivo* studies. Tomoregulin mRNA levels were first evaluated by Taqman analysis (data not shown). Among the prostate samples analyzed, the two tissue categories expressing most abundant tomoregulin transcripts are highlighted in bold.

The two tissue categories expressing most abundant tomoregulin transcripts are highlighted in bold. *Number of tomoregulin-positive libraries of libraries tested.

**Table 1.** Tissue distribution of tomoregulin mRNA by mining Incyte gene expression database (LifeSeq Gold 5.1)

<table>
<thead>
<tr>
<th>Tissue category</th>
<th>Positive libraries</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiovascular system</td>
<td>2/68</td>
<td>2</td>
</tr>
<tr>
<td>Connective tissue</td>
<td>0/47</td>
<td>0</td>
</tr>
<tr>
<td>Digestive system</td>
<td>0/148</td>
<td>0</td>
</tr>
<tr>
<td>Embryonic structures</td>
<td>1/21</td>
<td>3</td>
</tr>
<tr>
<td>Endocrine system</td>
<td>0/53</td>
<td>0</td>
</tr>
<tr>
<td>Exocrine glands</td>
<td>0/64</td>
<td>0</td>
</tr>
<tr>
<td>Genitalia, female</td>
<td>2/106</td>
<td>2</td>
</tr>
<tr>
<td><strong>Genitalia, male</strong></td>
<td><strong>19/114</strong></td>
<td><strong>29</strong></td>
</tr>
<tr>
<td>Germ cells</td>
<td>0/5</td>
<td>0</td>
</tr>
<tr>
<td>Hemic and immune system</td>
<td>0/159</td>
<td>0</td>
</tr>
<tr>
<td>Liver</td>
<td>1/35</td>
<td>1</td>
</tr>
<tr>
<td>Musculoskeletal system</td>
<td>2/47</td>
<td>3</td>
</tr>
<tr>
<td><strong>Nervous system</strong></td>
<td><strong>25/198</strong></td>
<td><strong>31</strong></td>
</tr>
<tr>
<td>Pancreas</td>
<td>0/24</td>
<td>0</td>
</tr>
<tr>
<td>Respiratory system</td>
<td>3/90</td>
<td>5</td>
</tr>
<tr>
<td>Sense organs</td>
<td>0/8</td>
<td>0</td>
</tr>
<tr>
<td>Skin</td>
<td>1/15</td>
<td>2</td>
</tr>
<tr>
<td>Stomatognathic system</td>
<td>0/10</td>
<td>0</td>
</tr>
<tr>
<td>Unclassified/mixed</td>
<td>2/13</td>
<td>4</td>
</tr>
<tr>
<td>Urinary tract</td>
<td>0/64</td>
<td>0</td>
</tr>
<tr>
<td>Totals</td>
<td>58/1,292</td>
<td>82</td>
</tr>
</tbody>
</table>

The expression of tomoregulin mRNA in a variety of human tissues was evaluated by quantitative real-time reverse transcription-PCR (RT-PCR) analysis (Taqman assay; Fig. 1). Consistent with the data in Table 1, Taqman analysis revealed the preferential expression of tomoregulin mRNA in prostate and prostate tumor tissues, and it is also highly expressed in late-stage prostate carcinoma including metastatic tissues from lymph node and bone.

**Figure 1.** Real-time RT-PCR (Taqman) analysis of tomoregulin mRNA in human normal and tumor tissues. Prostate tumor sections were microdissected to generate samples containing over 80% tumor cells. Total RNAs from prostate tumor tissues were purified from clinical samples, and normal human tissue RNA was purchased from a commercial vendor (Biochain, Hayward, CA). Solid bars, normal prostate (*N. prostate*); benign prostatic hyperplasia (*BPH Prostate*), and prostate tumor (*Tu prostate*). LNCaP (open bar) is a human prostate cancer cell line. Grey bars, brain and other tissues. The expression of tomoregulin mRNA normalized to GAPDH mRNA is shown as relative expression of tomoregulin mRNA.
the five prostate cell cultures, including PrEC (primary culture of human normal prostatic epithelial cells), BPH1 (T-antigen-immortalized benign prostatic hyperplasia cells), and the human prostate cancer cell lines LNCaP, PC-3, and DU 145, only LNCaP cells express significant levels of tomoregulin mRNA (as shown in Fig. 1).

Northern blot analysis on several cell lines confirmed that tomoregulin mRNA is expressed in LNCaP cells (Fig. 3A). A single species of tomoregulin mRNA at 2.2 kb was detected in LNCaP, but not in PrEC, DU 145, and PC-3 cells.

The expression of tomoregulin protein in LNCaP was evaluated by Western blot analysis using antibody 2H8 (Fig. 3B). Cell lysates prepared from PC-3 (lane 1) and Clone36 (lane 2) were included as negative control and positive control, respectively. The Clone36 cell line was generated by stably transfecting PC-3 cells with the tomoregulin expression vector (Materials and Methods). As shown in Fig. 3B, PC-3 cells do not express tomoregulin (lane 1). Clone36 cells overexpress the tomoregulin protein tagged by V5-His (48 kDa; lane 2). The recombinant extracellular domain of tomoregulin protein was detected at 40 kDa (lane 3). The endogenous full-length tomoregulin protein was detected as a single band of 43 kDa in LNCaP (passage 31) cell lysates (lane 4). We noticed that the levels of tomoregulin protein decreased with increasing passage number in cultured LNCaP cells (passage 31 > passage 60; data not shown). Lanes 6 and 7 are lysates derived from Clone36 tumors and PC-3 tumors, respectively. Interestingly, LNCaP xenograft tumors (lanes 8-10) express much higher levels of tomoregulin protein than LNCaP cells in tissue culture (lane 4).

Figure 2. Immunohistochemical staining of clinical samples from prostate cancer patients using anti-tomoregulin antibody Mab2H8. The tomoregulin-positive cells are stained in red. Top, lung, prostatic intraepithelial neoplasia (PIN), primary prostate carcinoma, and liver. Bottom, brain, lymph node metastasis of prostate cancer, bone metastasis of prostate cancer, and kidney.

Figure 3. Tomoregulin mRNA and protein expression in the LNCaP human prostate cancer cell line. A, Northern blot analysis of tomoregulin mRNA in human prostate normal epithelia cells PrEC (lane 1) and the human prostate cancer cell lines DU 145 (lane 2), LNCaP (lane 3), and PC-3 (lane 4). Total RNAs (12 μg per lane) were fractionated by a 1% agarose/formaldehyde gel and then transferred to a nylon membrane. The blot was hybridized with a tomoregulin-specific probe. Hybridization with actin serves as a control for equal loading. B, Western blot analysis of tomoregulin protein expression in cultured cells and xenograft tumors. Lane 1, PC-3 cell lysates (25 μg); lane 2, Clone36 cell lysates (25 μg); lane 3, recombinant extracellular domain of tomoregulin (5 ng); lane 4, LNCaP cell lysates (100 μg); lane 5, MW size standard; lane 6, Clone36 xenograft tumor lysates (70 μg); lane 7, PC-3 xenograft tumor lysates (70 μg); lanes 8 to 10, LNCaP xenograft tumor lysates (70 μg).
In view of these data, we have selected the LNCaP tumor xenograft model for in vivo studies.

111In-labeled tomoregulin antibody shows tumor-specific accumulation in a xenograft model of human prostate cancer. To determine whether the tomoregulin antibody 2H8 binds in vivo to tumor tissues expressing tomoregulin, biodistribution studies were done with systemically delivered radiolabeled 2H8 antibody. The anti-tomoregulin antibody, 2H8, or an irrelevant, isotype-matched control antibody, mouse IgG1, was labeled with 111In, each to a specific activity of ~1.4 mCi/mg and administered i.v. to mice bearing LNCaP s.c. tumors. At various time points (t = 4, 24, and 96 hours) following the injection, organ-bound radioactivity was determined in blood, tumor, liver, kidney, and brain. Both 2H8 and IgG control were cleared from the circulation in a similar fashion (Fig. 4A), however, the amount of IgG control retained in tumors did not change. Thus, 2H8, but not IgG1, showed a tumor-specific and time-dependent accumulation. At 96 hours after injection, the tumor retention of the 111In-labeled 2H8 in LNCaP tumors reached nearly 25% injected dose per gram of tissue (Fig. 4A). The very high tumor-to-blood ratio of 4:1 (Fig. 4B) further reinforces the targeting specificity of the antibody. There was no specific 2H8 accumulation in liver and kidney, highly vascularized tissues that do not express tomoregulin protein. Although 2H8 cross-reacts with the mouse tomoregulin protein (data not shown) and mouse tomoregulin is expressed in mouse brain (8), no specific accumulation of 2H8 was observed in mouse brain, most likely due to the inability of antibody to penetrate the blood-brain barrier. The same tumor localization data of 2H8 were reproduced in a second biodistribution study using nude mice s.c. implanted with Clone36 cells (data not shown).

Radioimmunotherapy with 90Y-labeled tomoregulin antibody inhibits growth of LNCaP tumors. To evaluate the efficacy of tomoregulin-based radioimmunotherapy, 2H8 was radiolabeled with the β-emitting isotope 90Y (t1/2 = 64 hours), and administered i.p. to nude, male, tumor-bearing mice. First, the potential toxicity from radiolabeled antibody was investigated in a dose-ranging study. LNCaP tumor–bearing mice (n = 5/group) were given a single i.p. injection of 45, 90, 128, or 170 μCi of 90Y-labeled 2H8. The mice were monitored for body weight and general clinical appearance. Evidence of toxicity from body weight loss was not observed and there were no animal deaths. Thus, all dose levels were tolerated. Interestingly, a dose-dependent antitumor effect was observed at doses ≥ 45 μCi (Fig. 5A). Next, mice bearing LNCaP tumors of 50 to 500 mm3 were given a single i.p. injection of 150 μCi of 90Y-labeled 2H8, 150 μCi of 90Y-labeled IgG1, or unlabeled 2H8 (n = 15/group). Tumor growth was monitored until ≥30% of the tumors in a treatment group exceeded 1,000 mm3. Radioimmunotherapy with both 90Y-labeled 2H8 and 90Y-labeled IgG1 at 150 μCi was well tolerated and resulted in significant efficacy (Fig. 5B and C). However, the antitumor effect of 90Y-labeled 2H8 treatment persisted much longer, resulting in a statistically significant difference in the tumor sizes between the 90Y-labeled 2H8–treated group and the 90Y-labeled IgG1–treated group. This result was confirmed by the tumor weights taken at necropsy on day 67 (P < 0.05; Fig. 5C).

All xenografts showed the same histology regardless of treatment group (data not shown). There was no increase in macrophages, etc. observed in tumors of animals treated with antibodies. Yet there was a significant difference in average viable weight (199.7 μg for 90Y-labeled 2H8–treated group versus 342.9 μg for 90Y-labeled IgG1–treated group).

Our results clearly show that the anti-tomoregulin antibody 2H8 specifically interacts with tomoregulin in vivo, leading to specific accumulation in the LNCaP tumors. Furthermore, radioimmunotherapy using 90Y-labeled 2H8 leads to a significant growth inhibition of established human tumor xenografts in nude mice, whereas indications of overt toxicity were not observed.

Discussion

Tomoregulin represents an attractive target for radioimmunotherapy of prostate cancer for the following reasons:

(a) As shown in our study tomoregulin is abundantly expressed in the prostate and prostate cancers, as well as in their lymph node and bone metastases. Other investigators have reported similar findings (11–13). Glynne-Jones et al. (11) analyzed 85 clinical samples by Taqman analysis and showed that tomoregulin mRNA is significantly overexpressed in prostate carcinomas when compared with their benign counterpart. Furthermore, there also seems to be a direct correlation between increasing tomoregulin
Tomoregulin-Targeted Radioimmunotherapy

Figure 5. Antitumor effect of the 90Y-labeled tomoregulin antibody, 2H8, against established LNCaP tumors. A, dose ranging study. DTPA-conjugated tomoregulin antibody (2H8) was radiolabeled with 90Y and administered i.p. at 45, 90, 128, and 170 μCi/mouse to mice bearing LNCaP tumors (50-350 mm³). A group treated with 2H8 (not DTPA conjugated, not radiolabeled) and a group without any treatment were included. No overt toxicity (animal deaths or excessive body weight loss) was observed in any of the groups. Points, group average (mean); bars, SE. B and C, efficacy study. On day 0, mice with tumors of 50 to 500 mm³ in volume were distributed in treatment and control groups (n = 15/group). 90Y-labeled 2H8 and 90Y-labeled IgG1 with the same approximate specific activity were administered as a single i.p. dose of 150 μCi. A group treated with 2H8 (not DTPA conjugated, not radiolabeled) and a group without any treatment were included. The mice were monitored for tumor growth (tumor volume) over time (B) and for final tumor wet weight (C). Asterisks indicate where group average tumor volume or tumor wet weight between 90Y-2H8 and 90Y-IgG was significantly different (P < 0.05). Mice receiving no treatment or unlabeled 2H8 were euthanized on day 40 due to tumor burden. Mice treated with 90Y-labeled antibodies were euthanized on day 67. Columns, group average (mean); bars, SE.

Tomoregulin has a growth promoting function similar to Follistatin, which was shown). The expression of tomoregulin mRNA in kidney that we detected in Taqman studies could not be verified by other methods. Multiple tissue Northern blots did not reveal kidney expression (data not shown), in line with the data by Glynne-Jones et al. (11). Therefore, the low signal in kidney detected in the Taqman study (Fig. 1) may be due to the ultrasensitive nature of Taqman assay. This assumption is supported by our immunohistochemical analysis showing little staining of human kidney by the 2H8 antibody and also by our biodistribution study showing no uptake of 2H8 in mouse kidney (Fig. 4). Because tomoregulin protein is detected in normal prostate, benign prostatic hyperplasia, prostatic intraepithelial neoplasia, and prostate tumors, it seems to be a prostate-specific differentiating antigen.

(c) Finally, the feasibility of targeting tomoregulin by radioimmunotherapy is warranted by the fact that tomoregulin is a plasma membrane protein and easily accessible to circulating radiolabeled antibodies. Fluorescence-activated cell sorting using 2H8 showed that tomoregulin protein is expressed on the cell surface of LNCaP and tomoregulin-transfected Clone36 cells but not in PC-3 parental cells (data not shown). The expression of tomoregulin mRNA in kidney that we detected in Taqman studies could not be verified by other methods. Multiple tissue Northern blots did not reveal kidney expression (data not shown), in line with the data by Glynne-Jones et al. (11). Therefore, the low signal in kidney detected in the Taqman study (Fig. 1) may be due to the ultrasensitive nature of Taqman assay. This assumption is supported by our immunohistochemical analysis showing little staining of human kidney by the 2H8 antibody and also by our biodistribution study showing no uptake of 2H8 in mouse kidney (Fig. 4). Because tomoregulin protein is detected in normal prostate, benign prostatic hyperplasia, prostatic intraepithelial neoplasia, and prostate tumors, it seems to be a prostate-specific differentiating antigen.

Tomoregulin-targeted radioimmunotherapy is warranted by the fact that tomoregulin is a plasma membrane protein and easily accessible to circulating radiolabeled antibodies. Fluorescence-activated cell sorting using 2H8 showed that tomoregulin protein is expressed on the cell surface of LNCaP and tomoregulin-transfected Clone36 cells but not in PC-3 parental cells (data not shown). Afar et al. (13) also showed that tomoregulin is located at the cell surface and is rapidly internalized at 37°C on antibody binding. It is important to note that tomoregulin is not a secreted protein like prostate-specific antigen and prostatic acid phosphatase. Targeting these secreted proteins may be problematic due to the potential binding capacity of circulating protein to the antibody (2).

The function of tomoregulin is currently unclear. It was reported that tomoregulin increases the survival of neurons from hippocampus and midbrain (8). Furthermore, the presence of the follistatin domains in tomoregulin may suggest that tomoregulin has a growth promoting function similar to Follistatin, which was
shown to be an antagonist of activin-mediated growth inhibition and seems to be overexpressed in melanoma and liver tumors (14, 15). However, tomoregulin exhibited antiproliferative activity when ectopically overexpressed in PC-3 and DU 145 cells (16). In our experiments, we were unable to detect any antiproliferative effect when tomoregulin was overexpressed in PC-3 cells. Furthermore, the addition of recombinant extracellular domain of tomoregulin to LNCaP or PC-3 cells did not alter the proliferative rate of these cells (data not shown) as these cells do not express the erbB-4/HER-4 receptor (6, 17).

For our biodistribution study (Fig. 4), 111In was used to monitor accumulation of the antibodies in various tissues. 111In-labeled 2H8 showed a time-dependent accumulation in tumor tissues expressing either the endogenous tomoregulin protein (LNCaP, Fig. 4) or the transfected tomoregulin protein (Clone36 model, data not shown). No antibody uptake was observed in mouse brain presumably due to exclusion of antibodies by the blood-brain barrier. Mouse liver and kidney had no uptake, although they are well vascularized. Although LNCaP tumors and Clone36 tumors have different degrees of vascularization, 2H8 showed similar biodistribution profiles in these two tumor models, suggesting that the targeting of 2H8 in vivo is determined by tomoregulin expression. In both models, the maximum tumor-specific accumulation of 2H8 reached 25% of the injected dose. This is comparable to biodistribution results using an anti–prostate-specific membrane antigen antibody (J591) in the same LNCaP model (18).

In summary, our work has established that tomoregulin is a good target for radioimmunotherapy of prostate cancer because it shows restricted expression in normal tissues and overexpression in prostate tissues with advanced tumor grade and that the presence of the tomoregulin protein in metastases was detected by immunohistochemistry. In addition, the high tumor-specific accumulation of 2H8 and the efficacy of 90Y-labeled 2H8 without overt toxicity make tomoregulin-targeted radioimmunotherapy an attractive approach for the treatment of advanced prostate cancer. A recent phase I clinical trial of radioimmunotherapy on androgen-independent prostate cancer has been reported using 90Y-labeled anti–prostate-specific membrane antigen humanized antibody J591 (20). Seventeen of 19 patients (89%) with bone lesions and only 9 of 13 patients (69%) with soft tissue lesions were accurately targeted by J591. Furthermore, signs of efficacy were only observed at doses at or above the maximal tolerated dose and, thus, an increased therapeutic window will be needed. A radioimmunotherapy targeting tomoregulin may offer a better therapeutic window. In addition, our expression database indicates that a subpopulation of patients express tomoregulin but not anti–prostate-specific membrane antigen, suggesting that patients who cannot be targeted by J591 could benefit from tomoregulin-targeted radioimmunotherapy.

In summary, our work has established that tomoregulin is a good target for radioimmunotherapy of prostate cancer because it shows restricted expression in normal tissues and overexpression in prostate cancer and metastases. Our in vivo data show that the radionabeled tomoregulin antibody localized to the tumor site, and that its strong tumor-specific accumulation resulted in significant growth inhibition of established LNCaP tumors, but produced no overt toxicity.

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