Immunological Responses in Human Papillomavirus 16 E6/E7-transgenic Mice to E7 Protein Correlate with the Presence of Skin Disease


ABSTRACT

The human papillomavirus (HPV) oncogenes, E6 and E7, are believed to contribute to the development of cervical cancers in women infected with certain HPV genotypes, most notably HPV-16 and HPV-18. Given their expression in tumor tissue, E6 and E7 have been implicated as potential tumor-specific antigens. We have examined an HPV-16 E6- and E7-transgenic mouse lineage for immune responses to these viral oncoproteins. Mice in this lineage express the HPV-16 E6 and E7 genes in their skin and eye, and on aging, these mice frequently develop squamous cell carcinomas and lenticular tumors. Young transgenic mice, which had measurable E7 protein in the eye but not in the skin, were immunologically naive to E7 protein. They mounted an immune response to E7 on immunization comparable to that of nontransgenic controls, suggesting a lack of immune tolerance to this protein. Older line 19 mice, which are susceptible to skin disease associated with transcription of the E6 and E7 open reading frames, had measurable E7 protein in their skin. These older transgenic mice spontaneously developed antibody responses to endogenous E7 protein, particularly in association with skin disease. Also detected in older mice were delayed-type hypersensitivity responses to E7. These finding parallel the humoral immune response to E7 protein in patients with HPV-associated cervical cancer and suggest that line 19 mice may provide a model for studying the immunobiology of HPV-associated cancers.

INTRODUCTION

A majority of cervical cancers contain HPV\(^3\) DNA, and between 60 and 80% of these contain DNA from the HPV-16 genotype (1), commonly integrated within the cellular genome. In HPV DNA-positive cervical cancers, transcription of the E6 and E7 ORFs of HPV is observed, and a critical role for these viral gene products in cervical cancer can be inferred from the preservation in each cancer of these ORFs (2). Additional evidence for the role of E6 and E7 comes from the observation that expression of the E6 and E7 ORFs in primary human epithelial cell cultures facilitates their immortalization (3). Furthermore, mice transgenic for E6 and E7 develop epidermal hyperplasia (4, 5) and are at increased risk of epithelial tumor development (6).

That E6 and E7 are expressed in cervical cancers indicates that these viral gene products are potential tumour-specific antigens that might be the target of host-protective immune responses. The increased incidence of cervical cancer in immunosuppressed renal transplant recipients (7) and in patients with HIV/AIDS (8, 9) suggests that a protective host response occurs in immunocompetent patients. Antibody to the E7 ORF of HPV-16 has been demonstrated more frequently in patients with HPV-16-associated cancer than in control subjects not expected to be exposed to HPV-16 (10); this is observed particularly in patients with invasive HPV-16-associated tumors. A role of E7-directed immune responses in tumor protection has been raised by studies in which animals immunized against E7 acquired resistance to challenge with tumor cells expressing E7 (11). We have sought to assess the role of E7-specific immunity in a relevant mouse model that closely approximates the natural course of disease seen with human cervical cancer, and in which the papillomaviral oncogenes play a causative role in tumorigenesis. Several lines of mice transgenic for the HPV-16 E6 and E7 ORFs driven from the αA-crystallin promoter have been described recently (4). One of these lines of mice (αAcrHPV16E6/E7-line 19) develops a skin pathology including hair loss, dermal thickening, papilloma development, and eventual skin cancer associated with increased levels of E6 and E7 mRNAs in the affected skin (12). This disease begins to appear at 3 months of age; by 1 year approximately 50% have abnormal skin. In the current study, we have characterized immunity to HPV-16 E7 protein in these mice and the relationship between any observed tolerance of, or immunity to, E7 and the development of the skin disease. As seen in cervical cancer patients, these mice were found to develop humoral and cellular immune responses against E7 protein, and this correlated with the presence of transgene-induced skin disease. These findings indicate that these HPV-16 transgenic mice may provide a useful model for studying the immunobiology of HPV-associated neoplasia.

MATERIALS AND METHODS

Mice. Nontransgenic FVB mice and αAcrHPV16E6/E7-line 19 mice derived from FVB mice and homozygous for a transgene that includes the E6 and E7 ORFs of HPV-16, driven by the αA-crystallin promoter, were held in standard American Association for Accreditation of Laboratory Animal Care approved mouse rooms under specific pathogen-free conditions.

Proteins and Peptides. A series of overlapping 18–26-mer peptides spanning the 98-amino acid predicted sequence of the E7 protein of HPV-16 (Fig. 1) were synthesized with the use of F-moc chemistry on an Applied Biosystems AB4341 synthesizer (Applied Biosystems, Foster City, CA) as described previously (13). Synthetic peptides BT12D (DRAHYNIVTFCCCKDCQAEPDAGIDGPAGEYM: single letter code) containing three B epitopes and a T-helper epitope from HPV-16 E7, FG10 (TRKSSRQGPDRAHYNIVTFCCCKD), including a HPV-1 gpl20 B epitope and a T-helper epitope from HPV-16 E7, and GP22 (QDIVHLHEPNQEPVYDLL, which includes a B epitope from HPV-18 E7 protein, were synthesized similarly. Peptides were purified by HPLC and analyzed as described previously (13). An HPV-16 E7 GST fusion protein was prepared in Escherichia coli and purified as described (14). The bacterially produced fusion protein MS2-E7(15) was prepared from E. coli as described (16). Baculovirus-derived E7 protein was prepared as described and used as a crude cell lysate (17). A highly purified (>95%) preparation of bacterially produced HPV-16 E7 protein was prepared as described (18).

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3 The abbreviations used are: HPV, human papillomavirus; ORF, open reading frame; DTH, delayed-type hypersensitivity; i.d., intradermally.
Epitope is ringed. The sequence of the synthetic GF109 that spans the HPV16 E7 molecule. Known as the T-helper epitope is shown below. The peptide BT12D that contains three B epitopes and 0.15 M NaCl with 0.1 ml of complete Freund's adjuvant, and boosted at days 14 and 28 with an equal amount of antigen in incomplete Freund's adjuvant. Sera were obtained from mice at day 42.

Assay of E7 Protein. Tissues for analysis were snap frozen in solid CO2-ethanol and held at ~70°C for analysis. Tissues were pulverized in a chilled mortar and pestle and assayed for HPV-16 E7 and HPV-18 E7 protein as a control, with the use of an ELISA capture assay standardized on HPV 16 E7 fusion protein essentially as described previously (14), except that extracted samples were boiled for 5 min with 0.1% SDS prior to analysis, which stabilizes the E7 protein (data not shown). Limits of E7 protein detection were established by performing the ELISA capture assay in parallel with serial dilutions of bacterially synthesized E7 fusion protein that had been purified and quantitated (see Ref. 14).

Antibody to E7 Protein and Peptides. An ELISA was used to measure antibody as described previously (16). In brief, peptides and proteins were dissolved in carbonate buffer (pH 9.4) and allowed to adsorb to 96-well plates. Plates were blocked with 2% BSA and exposed for 1 h to sera diluted 1:20 (or otherwise stated) in PBS-2% BSA. Plates were washed extensively with PBS-0.1% gelatin-0.1% Tween 20, exposed to goat anti-mouse immunoglobulin or goat anti-mouse IgG (Sigma Chemical Co., St. Louis, MO), washed additionally, and developed with 2,2'-azino-bis(3-ethylbenzthiazoline-6-sulfonic acid) substrate. Absorbance measurements (414 and 620 nm) were assessed after 5–30 min of incubation with substrate on a Titertek Multiskan dual wavelength spectrophotometer (LabSystems, Helsinki, Finland).

DTH to E7 Protein. Mice were given 400 ng pertussigen (CSL, Melbourne, Australia) i.v. in 0.1 ml PBS (19) and immediately challenged i.d. in the left ear with 0.5–2.5 mg protein in 10 μl PBS. Ear thickness was assessed with the use of spring-loaded calipers (Mitutoyo 2046F) 48 and 96 h after challenge and was reported as the difference between the challenged and the control ear.

RESULTS

Induced Antibody Response to HPV-16 E7 Protein in Line 19 Mice. To analyze the potential of the αAcryHPV16E6/E7-line19 (herein referred to as line 19 mice) to respond immunologically to E7 protein, young transgenic and nontransgenic animals were immunized with E7 protein and sera monitored for E7-specific antibodies. These transgenic mice developed E7-specific antibodies as did E7-immunized nontransgenic mice (Table 1). Furthermore, the transgenic and nontransgenic mice responded to similar linear epitopes from E7 (Fig. 2A), these epitopes being equivalent to those recognized by sera from E7-immunized mice of other haplotypes (H-2b, H-2d, H-2s, H-2k; Refs. 16, 20). Consistent with these observations, both the transgenic and nontransgenic mice developed E7-specific antibodies when immunized with an oligopeptide, BT12D, containing a known E7-specific T-helper epitope and the above noted E7-specific B cell epitopes (Table 1). Thus, the humoral responses of transgenic and nontransgenic mice were indistinguishable from each other.

E7 Protein Expression in the Skin of Line 19 Mice. Self-tolerance is argued to occur through the recognition of self-peptides expressed during postnatal development within immunosurveys in the thymus (central or deletional tolerance) or other tissues (peripheral tolerance). Our E7 immunization studies suggested an absence of central and peripheral tolerance to E7 in the line 19 transgenic mice. To address whether this absence of tolerance correlated with an absence in the expression of E7 protein in immunosurveys, we measured E7 protein levels in various organs of line 19 mice utilizing an ELISA-capture assay sensitive to 0.05 ng E7/mg cellular protein. No E7 protein was detected in any tissues from nontransgenic mice (data not shown). E7 protein was found in the eye of line 19 mice at an early age (Table 2). This was anticipated given that the transgene is under the control of the α-crystallin promoter and is actively transcribed in the lens by day 17 in embryogenesis (4). Expression of E7 protein in the lens, however, would not be predicted to induce tolerance given that the lens is an immunoprivileged site. No E7 protein was detected in any other tissue of young line 19 mice, including the liver, spleen, brain, stomach, skin and, importantly, the thymus (Table 2; data not shown).

In our previous study, we demonstrated increased levels of E6 and E7 mRNAs in the abnormal skin and skin cancers in older line 19 mice (12). Skin samples from line 19 mice were, therefore, tested for E7 protein. Some older (>28 weeks old) mice were found to be positive for E7 protein in normal and diseased skin, as well as in a skin

### Table 1 Induced immune response to E7 proteins and peptides in young line 19 and FVB mice

<table>
<thead>
<tr>
<th>Immunogen</th>
<th>Mouse strain (no. of mice)</th>
<th>BSA</th>
<th>E7</th>
<th>GST-E7</th>
<th>MS2-E7</th>
<th>BT12D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saline</td>
<td>Line 19 (3)</td>
<td>0.002 +0.000</td>
<td>0.006 ±0.001</td>
<td>0.018 ±0.005</td>
<td>0.041 ±0.015</td>
<td>0.002 ±0.000</td>
</tr>
<tr>
<td>Saline</td>
<td>FVB (3)</td>
<td>0.003 ±0.001</td>
<td>0.003 ±0.001</td>
<td>0.005 ±0.001</td>
<td>0.016 ±0.003</td>
<td>0.002 ±0.000</td>
</tr>
<tr>
<td>E7</td>
<td>Line 19 (3)</td>
<td>0.001 ±0.000</td>
<td>0.027 ±0.004</td>
<td>0.055 ±0.014</td>
<td>0.077 ±0.020</td>
<td>0.015 ±0.001</td>
</tr>
<tr>
<td>GST-E7</td>
<td>Line 19 (3)</td>
<td>0.005 ±0.001</td>
<td>0.070 ±0.037</td>
<td>0.095 ±0.039</td>
<td>0.095 ±0.038</td>
<td>0.066 ±0.007</td>
</tr>
<tr>
<td>GST-E7</td>
<td>FVB (3)</td>
<td>0.001 ±0.000</td>
<td>0.347 ±0.022</td>
<td>0.481 ±0.018</td>
<td>0.354 ±0.028</td>
<td>0.119 ±0.053</td>
</tr>
<tr>
<td>GST-E7</td>
<td>FVB (2)</td>
<td>0.001 ±0.000</td>
<td>0.350 ±0.026</td>
<td>0.372 ±0.007</td>
<td>0.384 ±0.068</td>
<td>0.189 ±0.150</td>
</tr>
<tr>
<td>GST-E7</td>
<td>FVB (4)</td>
<td>0.001 ±0.000</td>
<td>0.194 ±0.003</td>
<td>0.211 ±0.007</td>
<td>0.172 ±0.017</td>
<td>0.229 ±0.012</td>
</tr>
<tr>
<td>GST-E7</td>
<td>mAb α E7</td>
<td>0.001</td>
<td>0.205</td>
<td>0.243</td>
<td>0.171</td>
<td>0.221</td>
</tr>
</tbody>
</table>

*Absorbance units (414–620 nm). Note the small but significant difference in reactivity of the saline/line 19 versus saline/FVB mouse sera to E7 substrates was not reproduced with additional bleeds from these same mice.

*Produced using a baculovirus vector.

*Control result with E7-specific mAb 6D (15) used at 1:1000.
E7 IMMUNOGENICITY IN HPV-16-TRANSGENIC MICE

Some older line 19 mice and, particularly, in older line 19 mice with skin disease (Fig. 3; see also Fig. 2B for data on smaller groups of additional animals). This correlation between skin disease and serum antibody to E7 protein was significant (Table 3; \( P = 0.007 \)) and reproducible among multiple independent ELISA assays on the same group of sera (data not shown). Thus, spontaneous humoral responses to E7 protein occur in the line 19 mice and correlate with the presence of skin disease.

The properties of the E7-reactive sera from these unimmunized line 19 mice differed from that of E7-immunized syngeneic mice in two respects: (a) the E7-reactive sera from unimmunized line 19 mice had antibody titers significantly lower than that in sera from E7 immunized mice. This is deduced from the reproducible difference in the strength of ELISA readouts against GST-E7 substrate for these two populations of animals as reported in Fig. 3 (mean absorbance units for the seven unimmunized older animals with skin disease = 0.180; note a similar mean value of 0.130 was found for a smaller group of 3 animals evaluated in Fig. 2B) versus Table 1 (mean absorbance units for E7-immunized line 19 mice = 0.481); and (b) the B-cell epitopes on E7 recognized by the E7-reactive, unimmunized line 19 mice mapped to the COOH terminus of E7 (Fig. 2B), and, therefore, differ from the NH2 terminus-specific epitopes predominantly recognized in E7-immunized FVB mice (Fig. 2A).

Spontaneous Delayed-Type Hypersensitivity to E7 Protein. Ultimately, we are interested in understanding whether immune responses against E7, spontaneous or induced, can provide protection against the development of HPV-associated neoplasia. Such protective immune responses are thought to primarily rest in the cellular arm of the immune system. To test whether spontaneous cellular immune response to E7 protein occur in the line 19 mice and correlate with the presence of skin disease.

Table 2 Immunoreactive E7 protein in the tissues of line 19 mice

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Young mice (4–7 weeks)</th>
<th>Old mice (26–52 weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye</td>
<td>1/1*</td>
<td>NT</td>
</tr>
<tr>
<td>Eye tumor</td>
<td>2/5</td>
<td>3.8–5.2</td>
</tr>
<tr>
<td>Normal skin</td>
<td>0/20</td>
<td>6/22</td>
</tr>
<tr>
<td>Diseased skin</td>
<td>7/14</td>
<td>0.3–11.5</td>
</tr>
<tr>
<td>Skin tumors</td>
<td>1/3</td>
<td>0.74</td>
</tr>
</tbody>
</table>

\( ^* \) Number of positive samples/total number of samples tested; NA, not available; NT, not tested.
\( ^\# \) Results are expressed as ng immunoreactive E7 protein (iE7) per mg cellular protein in positive samples. The lower detection limit of the assay is 0.05 ng iE7/mg cellular protein.
\( ^\dagger \) Results from four eyes assayed together.

tumor. The highest levels of E7 observed in the skin of line 19 mice were 4-fold lower than levels in the CaSki cervical carcinoma cell line (50 ± 10 ng E7/mg cell protein). In contrast, skin samples from young (7–13-week-old) line 19 mice had undetectable E7 protein. Thus, expression of detectable levels of E7 protein was found to occur at a nonimmunoprivileged site specifically in older mice.

Spontaneous Antibody Response to E7 Protein and Peptides. Given the absence of tolerance in line 19 mice and the adult onset expression of E7 protein in the skin, we addressed whether these transgenic mice developed spontaneous immune responses to endogenously expressed E7 protein as a function of age. Humoral immune responses to E7 were assessed in young (4–7 weeks) and older (26–30 weeks) line 19 mice. E7-specific antibodies were found in...
responses to endogenous E7 protein occur in our line 19 transgenic mice, experiments measuring DTH to HPV-16 E7 protein were performed, with the use of an ear challenge assay (Table 4). DTH is thought to represent antigen-specific cytokine-mediated inflammation, particularly involving Th1 type cytokines, in this case in response to endogenous E7 protein. DTH responses to E7 have been previously noted in mice that had received grafts of E7-positive cells (21). In our hands, positive DTH responses peaking at 48–96 h and specific to GST-E7 protein were observed in 3 of 4 older line 19 mice. Two of these DTH-positive animals also had skin disease and E7-specific serum antibodies. None of the younger mice, or the nontransgenic controls, developed DTH responses against E7. These results indicate that unimmunized older line 19 mice may develop a cellular immune response to E7 protein.

**DISCUSSION**

In this study we have demonstrated that a line of mice transgenic for HPV-16 E6 and E7 oncogenes develop spontaneous immune responses to E7 that correlate with the presence of skin disease. Unlike in E7-immunized mice challenged with transplantable tumors transduced to express E6 or E7 (11, 22, 23), the line 19 mice with spontaneous immune responses to E7 are not protected against the development of HPV-16-associated cancer. This finding parallels observations with cervical cancer patients in which there is a weak and inconsistent antibody response to E7 protein (24). We therefore believe that these mice may provide a valuable tool with which to study the immunobiology of HPV-16-associated cancer.

We were surprised initially to find an absence of tolerance to the E7 transgene in the line 19 mice. Determinants of the development of tolerance or immune responsiveness to transgenic proteins are uncertain. Deletional B- and/or T-cell tolerance is observed generally when the protein is expressed in a wide range of tissues from a strong constitutive promoter (25), whereas functional silencing of T or B cells (anergy; Ref. 26) or developing immunity (27, 28) has been observed in transgenic models in which there is tissue-specific expression of the transgene protein. In a number of transgenic mouse models, development of immunity or tolerance to the transgene product has been held to be a consequence of the level and/or timing of transgene expression (29, 30, 31). In this regard, the absence of tolerance to E7 in the line 19 mice correlated with an absence of detectable E7 protein expression in neonatal thymus (data not shown) and in all other tissues tested from young animals with the exception of the lens, an immunoprivileged site. The lack of E7 expression in immunosurveyed tissues during the time when deletional tolerance occurs provides one likely explanation for the absence of B- and T-cell tolerance in these animals.

We observed a correlation between skin disease and spontaneous immune responses to E7 protein in older line 19 mice (Table 3). The adult onset immune responses may reflect the observed increases in the levels of E7 protein expressed in immunosurveyed tissues (Table 2). However, the molecular mechanisms for this increased expression of E7 protein are not known at this time. Possible mechanisms include amplification of the transgenes, increased transcription of E7, or changes in the stability of E7 protein. Alternatively, the adult onset immune responses may represent an altered sensitivity of the immune system to presentation of E7-specific epitopes, perhaps mediated by cytokine induction resulting from skin wounding.

Despite the evidence for spontaneous humoral and cellular immune responses to E7 (Fig. 3; Tables 3 and 4), the line 19 mice develop squamous cell carcinomas in which the E7 oncoprotein is expressed (12). Thus, the spontaneous immune responses are not protective. It is clear from other studies that mice can develop protective immunity when E7 is presented optimally (11, 22, 23). The lack of protective immunity in the line 19 mice may reflect the nature of E7 presentation by the skin or tumor cells to the immune system. For instance, were E7 presented in line 19 mice by E7-positive keratinocytes (Table 2), which are nonprofessional antigen-presenting cells, this presentation may be suboptimal. We found the strength of the E7-specific spontaneous humoral immune responses in line 19 mice (Table 3) to be well below that seen in mice immunized with E7 (Table 1). This low level spontaneous immune response may not be sufficient to provide protective immunity. Additionally, the E7 reactive sera from the older, unimmunized line 19 animals predominantly recognized linear epitopes at the COOH terminus of E7 (GF107, GF108, and GF109; Fig. 2B), a region likewise recognized by sera from CBA (H-2k) mice seeded with mouse L fibroblasts expressing the E7 gene (20). In contrast, the E7-specific epitopes (residing within peptides GF101, GF102, GF105, and GF106) strongly recognized by the E7-immunized transgenic and nontransgenic mice (Fig. 2A) lie in the NH2 terminus of E7 protein. These findings suggest differential processing or presentation of E7 protein by professional versus nonprofessional antigen-presenting cells, and this difference could contribute to the absence of protective immunity. A better understanding of the immunobiology of the line 19 mice may provide insight into how the immune system, when faced with the suboptimal presentation of papillomaviral antigens, can be induced to generate protective immunity against HPV-associated cancer.

**REFERENCES**


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Table 4  DTH to HPV-16 E7 protein in young and old line 19 transgenic mice and FVB controls

<table>
<thead>
<tr>
<th>Ear challenge</th>
<th>Old line 19</th>
<th>Young line 19</th>
<th>Old FVB</th>
</tr>
</thead>
<tbody>
<tr>
<td>GST-E7</td>
<td>15 ± 4 (4)b</td>
<td>3 ± 1 (4)</td>
<td>3 ± 1 (4)</td>
</tr>
<tr>
<td>GST</td>
<td>2 ± 2 (3)</td>
<td>3 ± 1 (4)</td>
<td>6 ± 3 (3)</td>
</tr>
<tr>
<td>GST-seed</td>
<td>−1 ± 1 (4)</td>
<td>2 ± 2 (4)</td>
<td>0 ± 1 (4)</td>
</tr>
</tbody>
</table>

*Δ Ear thickness (mm × 10^2 ± 1 SEM), (n)*

* a Average of the difference between the challenged and control ear at day 4. n, number of mice/group. As positive controls, two E7-immunized line 19 mice gave DTH responses (Δ ear thickness) of 15.

* b P < 0.01 compared with the control groups.
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