1. ABSTRACT

Human papillomaviruses (HPV), particularly HPV type 16, are the primary etiologic agent of cervical cancer. Thus, HPV-associated cervical malignancies might be prevented or treated by induction of the appropriate virus-specific immune responses in patients. HPV capsid proteins including L1 and L2 proteins have been shown to generate neutralizing antibodies against HPV particles in vaccinated individuals. Furthermore, HPV oncogenic proteins such as E6 and E7 proteins are important in the induction and maintenance of cellular transformation and are co-expressed in the majority of HPV-containing carcinomas. They represent ideal targets for the development of therapeutic vaccines against HPV infections and HPV-associated neoplasia. Vaccines targeting these proteins may provide an opportunity to control HPV-associated malignancies. Genetic immunization with naked DNA has emerged as an important strategy for vaccine development. Plasmid DNA encoding antigen of interest, such as capsid protein L1 and L2 (for preventive vaccines) and non-structural proteins E6 and E7 (for therapeutic vaccines) enters the host and stimulates an antigen-specific humoral and cellular immune response. Various strategies to enhance preventive and therapeutic effects of DNA vaccines are currently under active investigation. Should they fulfill their promise, these DNA vaccines may prevent HPV infection or control HPV-related cervical lesions.

2. INTRODUCTION

2.1. The Role of Human Papillomavirus in Cervical Cancers

Cervical cancer is the second leading cause of cancer death in women worldwide, with approximately 500,000 women developing the disease annually. Despite the availability of cervical cancer screening in the US, the
incidence of invasive cervical cancer does not seem to be diminishing (SEER Cancer Statistic Review). Over the past 15 years, epidemiologic/virologic data have identified a clear and consistent association of HPV infection with the development of cervical cancer. The evidence linking HPV to cervical cancer comes from a wide variety of epidemiologic and laboratory studies. More than 99% of cervical cancers and their precursor lesions, squamous intraepithelial lesions (SIL), contain HPV DNA (1). Furthermore, molecular, biochemical, and cellular studies have demonstrated that E6 and E7, two HPV gene products that are consistently expressed in precursor lesions (SIL) and cervical cancer, lead to malignant transformation of epithelial cells (for review, see (2)). E6 binds, inactivates, and promotes the degradation of p53, while E7 binds and inactivates pRB. Although over a hundred HPV genotypes have been identified, about 80% of cervical cancer is associated with four “high risk” types of HPV (types 16, 18, 31, 45) and the remaining cases are associated with a dozen other oncogenic types (for review, see (2, 3)). HPV-16 is present in approximately 50% of all cervical cancers (4) and is consequently the focus of many recent HPV vaccine developments.

2.2. Events in the Progression from HPV Infection to Cervical Cancer

Clinical, pathologic, and virologic studies have defined a clear progression of events in the development of cervical cancer. The pathogenesis of cervical cancer is initiated by HPV infection of cervical epithelium during sexual intercourse. The majority of genital HPV infections are transient. However, a fraction of infections persist and initiate transformation events within the cervical epithelium. Initial changes in the cervical epithelium, pathologically classified as low grade squamous intraepithelial lesions (LSIL, or CIN 1), are associated with continued viral replication and virus shedding (for review, see (5, 6)). In a study of 241 cytologically normal women recruited in a sexually transmitted disease clinic, the cumulative incidence of HSIL (CIN 2-3) at 2 years was 28% in HPV-positive women compared to 3% in HPV-negative women (7). The progression from HSIL to invasive cancer occurs at a high frequency. Progression is frequently associated with conversion of the viral genome from an episomal form to an integrated form, along with deletion or inactivation of E2, a negative regulator of E6 and E7 expression (5). Development of invasive cancer requires additional genetic events facilitated by E6 and E7-mediated inactivation of the genome guardians p53 and pRB, genomic instability, and suppression of apoptosis (5).

The well-defined virologic, genetic, and pathologic progression of HPV – from initial infection to lesion formation to malignant tumor formation – and the limited number of well-defined foreign (viral) antigens provide an unique opportunity to evaluate intervention with therapeutic vaccines at various stages of HPV infection and tumorigenesis.

2.3. HPV Virus-Like Particles (VLPs) as Preventive Vaccine for HPV-Associated Lesions

HPV virus-like particles have emerged as an exciting candidate prophylactic HPV vaccine. Prophylactic vaccine development is complicated by the lack of animal models for the genital mucosatropic HPV types and by the difficulty in propagating the virus in culture. These difficulties have been partially overcome using cutaneous and mucosal animal papillomaviruses as models and by the development of virus-like particles (VLPs). The papillomavirus major capsid protein L1 spontaneously assembles to form empty capsids, known as virus-like particles (VLPs) when expressed in mammalian (8, 9), insect (10), yeast (11) or bacterial cells (12). Parenteral injection of these VLPs elicits high titers of serum neutralizing antibodies and protection from experimental challenge with infectious virus in several animal papillomavirus models, in the absence of the potentially oncogenic genome (13-17). Protection from experimental infection by cottontail rabbit papillomavirus (CRPV) or canine oral papillomavirus (COPV) following passive transfer of IgG from immunized animals to naive animals has been demonstrated in rabbits and dogs respectively (15, 16). This indicates that cell-mediated effector immune responses are not required for protection from experimental infection.

Although VLP vaccination provides immunity from experimental inoculation, it is unclear whether this extends to protection against natural transmission of genital HPV. To completely prevent sexual transmission of genital HPV infection, neutralizing antibodies must act at mucosal surfaces that are the natural site of infection. Antibodies both pass from plasma into genital secretions and are synthesised by local plasma cells (18, 19). The plasma cell precursors that migrate to the genital tract derive primarily from mucosal lymphoid tissues and predominantly secrete IgA. Induction of these cells requires direct immunization of the mucosa-associated lymphoid tissue and in several experimental systems, nasal instillation was found to be the most effective route of immunization to generate specific antibodies in genital secretions in mice and in monkeys (20, 21).

In previous studies, systemic immunization of mice with purified HPV VLPs induced no detectable mucosal IgA antibodies and low titers of IgG (20, 22). Further, low titers of VLP-specific IgG, and no IgA, were detected in cervicovaginal lavage of parenterally immunized monkeys (23). Although these experiments in monkeys showed that transudated IgG alone partially neutralized HPV-11 in vitro, the mucosal antibody response was short-lived (23). Local, sustained production of secretory IgA (sIgA) and/or specific IgG are likely required for long lasting sterilizing immunity. Only nasal immunization using HPV16 VLPs has been shown to induce significant and sustained titers of HPV16 neutralizing antibodies in both serum and mucosal secretions of mice (12, 20). Thus, the route of administration may be important for generating protective humoral immune responses.

2.4. HPV Oncogenic Proteins, E6 and E7, as Targets for Immunotherapy for HPV-Associated Cervical Malignancies

Since E6 and E7 are consistently expressed in most cervical cancers, they represent promising targets for
HPV DNA vaccines

the development of antigen-specific therapeutic vaccines. While most tumor specific antigens are derived from normal or mutated proteins, E6 and E7 are completely foreign viral proteins, and therefore may harbor more antigenic peptides/epitopes than a mutant (i.e. p53) or reactivated embryonic protein (i.e. MAGE-1). Furthermore, since E6 and E7 are required for the induction and maintenance of malignant phenotype of cancer cells (24), cervical cancer cells cannot evade an immune response through antigen loss. Finally, studies in animal models suggest that vaccination targeting the papillomavirus early proteins such as E7 can generate therapeutic as well as protective effects (25). Therefore, E6 and E7 proteins represent good targets for developing antigen-specific immunotherapies or vaccines for cervical cancer. In our studies, we have focused on E7 because it is more abundantly expressed, better characterized immunologically and its sequence is more conserved than the E6 gene (26).

Various forms of vaccines, such as vector-based vaccines, tumor-based vaccines, DNA based vaccines and protein/peptide-based vaccines have been described in experimental systems targeting HPV-16 E6 and/or E7 proteins (27-31).

2.5. Importance of Cell-Mediated Immune Responses in Controlling Established HPV Infections and HPV-Associated Neoplasms

Findings from several studies suggest that cell-mediated immune responses are important in controlling both HPV infections and HPV-associated neoplasms (for review, see (32)). For example, the prevalence of HPV-related diseases (infections and neoplasms) is increased in transplant recipients (33) and human immunodeficiency virus (HIV) infected patients (34, 35), both of whom are known to have impaired cell-mediated immunity. Furthermore, animals immunized with non-structural viral proteins are protected from papillomavirus infection or the development of neoplasia. Immunization also facilitates the regression of existing lesions (36, 37). Infiltrating CD4+ (T helper cells) and CD8+ (cytotoxic T cells) T cells have been observed in spontaneously regressing warts (38); in addition, warts in patients who are on immunosuppressive therapy often disappear when treatment is discontinued (for review, see (39)). Therefore, effective HPV therapeutic vaccines should generate HPV-specific cell-mediated immune responses, particularly T cell-mediated immune responses.

2.6. Importance of Dendritic Cells in Mediating Immune Responses

DCs are the most potent professional APCs that prime helper and killer T cells in vivo (for review see (40-42)). DCs can stimulate T cells because of their high levels of MHC-I and MHC-II molecules, co-stimulatory molecules (i.e. B7), and adhesion molecules such as intercellular cell adhesion molecule-1 (ICAM-1), ICAM-3, and lymphocyte function-associated antigen-3. DCs perform a series of coordinated tasks in order to efficiently present antigens. Immature DCs develop from hematopoietic progenitors and are strategically located at body surfaces and in the interstitial spaces of many tissues. At these locations, DCs are equipped to capture antigens and to produce large numbers of immunogenic MHC–peptide complexes. In the presence of maturation-inducing stimuli such as inflammatory cytokines or stimulation via CD40 (43), DCs upregulate adhesion and costimulatory molecules to become more potent, terminally differentiated stimulators of T cell immunity. DCs also migrate to secondary lymphoid organs to select and stimulate antigen-specific T cells (44). Thus, many therapeutic vaccine strategies have focused on targeting antigen to professional APCs, such as DCs, and enhancing antigen processing and presentation in DCs in order to augment T-cell mediated immune responses.

2.7. Advantage of DNA Vaccine Vectors

The strategy behind genetic immunization is simple: injection of a DNA plasmid encoding a desired protein into the skin or muscle of the host elicits high efficiency expression of the polypeptide antigen of interest; antigen presentation by transfected cells promotes a cellular and humoral immune response against the antigen.

There are a few essential features of DNA plasmids used for vaccination. DNA vaccines comprise an antigen gene of interest cloned into a bacterial plasmid engineered for optimal expression in eukaryotic cells. Plasmid DNA has a bacterial origin of replication, an antibiotic resistance gene to enable plasmid selection during bacteria culture, a eukaryotic promoter, and poly A sequences to stabilize mRNA transcripts. Constructs also contain unmethylated, palindromic sequences containing cytidine-phosphate-guanosine oligonucleotides (CpG-ODN), to activate an antigen-independent immune response. Via the toll-like receptor (45-47), CpG motifs directly stimulate B cells to proliferate and secrete antibodies (48) and APCs to secrete cytokines (49-51), which can activate NK cells (52-55) and T cells (56-58). CpG motifs have exhibited adjuant properties when administered with peptide (59) and human papillomavirus-like particles (60), and may contribute similarly to the immunogenicity of DNA vaccines (61-63). The effects of CpG motifs can be maximized by optimal bases flanking the CpG dinucleotide, (possibly GTCGTT in humans (64)), a TpC dinucleotide on the 5' end and a pyrimidine rich 3' end (64-66). Studies have shown that the most immunogenic ODN have two or three CpG motifs spaced with at least two intervening bases, ideally, Ts (64-66). Additionally, eradication of suppressive motifs from the plasmid backbone may yield a significantly more immunogenic vaccine (67).

Various strategies to optimize the DNA vector are currently under investigation, including manipulation of gene regulatory elements, construction of multivalent vaccines, and manipulation of heterologous genes to modulate immune response (for review, see (68)).

3. DNA VACCINES for HPV

Although many types of vaccines are currently under investigation, DNA vaccination is an especially
Figure 1. Mechanisms of DNA Vaccine Antigen Presentation. Antigen can be presented to T cells by APCs or somatic cells directly transfected with antigen. Conversely, these cells, particularly somatic cells, may deliver antigen to another APC, via secretion or uptake upon programmed cell death of the transfected cell. This APC may then present antigen of interest to CD4⁺ and CD8⁺ T cells.

3.1. Mechanism of Antigen Presentation

There are at least two mechanisms by which the antigen encoded by the foreign genes in the bacterial plasmid is processed and presented to the host immune system, direct priming and cross-priming (see Figure 1 for details). As described earlier, overwhelming evidence suggests that DCs are the principal cells initiating an immune response after vaccination with naked DNA. DCs transfected with antigen can present antigen to T cells via direct priming. Additionally, DCs phagocytose and process peptides/proteins from apoptotic/necrotic somatic cells and other DCs (71). This process of DCs taking up antigen from somatic cells or other DCs and then processing the exogenous antigen via the MHC class I pathway for presentation to CD8⁺ T cells is known as cross-priming.

3.2. Administration of DNA vaccines

DNA vaccines can be administered to the host by intramuscular injection, intradermal injection via hypodermic needle or via gene-gun (a ballistic device for delivering DNA-coated gold particles into the epidermis), intravenous injection, intranasal delivery or biojector delivery (for reviews, see (70, 72)). Intramuscular and intradermal injection have been shown to induce an immune response and antitumor effect (73-80). Intradermal DNA vaccination using via gene-gun has generated particularly effective antitumor immunity in several murine tumor models (81, 82).

Information about the mechanisms of DNA vaccination by intramuscular injection or gene gun delivery is accumulating. Following intramuscular injection, some of the myocytes are transfected by the DNA vaccines, and the transfected myocytes produce protein and transfer the antigens to the bone marrow-derived professional APC (cross-priming)(83). Alternatively, the injected DNA may
move as free DNA through blood to the spleen where DCs initiate responses (72). Following gene-gun delivery, the epidermal Langerhans cells are transfected by the DNA vaccine and then serve as APCs. The DCs of the skin carry the antigen from the skin to the draining lymph nodes, where the antigen-loaded DCs activate the naïve T cells (84). The method of DNA inoculation (gene gun versus intramuscular injection) helps determine whether T-cell help will be primarily type 1 or type 2 (for review see (72)). The form of the DNA-expressed antigen (cell-associated versus secreted) may also influence T cell response (for review see (72)).

Recently, needle-free injection devices have emerged as effective, safe, less painful devices for delivering DNA vaccines. The Biojector (Bioject Inc., Portland OR) uses a CO$_2$ cartridge to propel vaccine intradermally or intramuscularly. This device has been shown to enhance antigen-specific antibodies in rabbits and rhesus monkeys (85-89). Observed increase in immunogenicity compared to needle injectors may result from the Biojector improving distribution of vaccine at the site of administration, spreading antigen to APCs in multiple tissue layers (90, 91). The Biojector is additionally advantageous because it uses disposable cartridges, which reduces the risk of spreading bloodborne pathogens by needle reuse, inadvertent needlestick, or improper needle disposal. The Biojector has been employed in clinical studies, which observed no adverse results or toxicity (86, 87, 92, 93). Thus, the Biojector may be a potent, safe, more patient-friendly mode of DNA vaccine administration.

Conceptually, HPV vaccines can be classified into two major categories: Preventive HPV vaccines and Therapeutic HPV vaccines.

### 3.3. Preventive HPV DNA vaccines

Immunoprophylactic vaccines induce a humoral immune response to prevent HPV infection. These vaccines generate neutralizing antibodies that can prevent viral particles from infecting host cells. Administration of DNA plasmid vaccines has been shown to induce a strong antibody response that is protective in a variety of animal models. DNA vaccination stimulates IgG, IgM, and IgA production, and the subclass of antibodies produced, IgG1 or IgG2a, depends on the route of DNA vaccination. Antibody production increases proportionally with dosage, in both a single injection and multiple injections by various routes of immunization (73, 94). Peak antibody responses typically occur 4-12 weeks post-vaccination (73, 94), but the magnitude and duration of antibody response to DNA vaccines is extremely variable, changing with the model system and vaccine used. Preventive DNA vaccine development has been complicated by the lack of animal models for the genital mucosatropic HPV types and by difficulty in propagating the virus in culture.

Choice of antigen is important for prophylactic vaccines. Early gene-based vaccines have been shown to generate only partial protection in studies with prophylactic DNA vaccines administered via gene gun to rabbits (95-98), although prophylactic immunity has been enhanced by priming DNA vaccination sites with a GM-CSF-expressing vector (99). The relatively weak prophylactic effects observed after E6 and E7 vaccine administration are probably a result of the absence of E6 and E7 on the viral surface. Conversely, L1 and L2, capsid proteins expressed on the viral surface, have generated highly potent humoral responses when administered in DNA vaccines, and are therefore the antigens generally employed in prophylactic vaccines for HPV.

Many prophylactic studies involving the intramuscular injection of capsid protein L1-encoding DNA have successfully generated an L1-specific immune response. For example, BALB/c (100, 101) and C57BL/6 mice (102) intramuscularly immunized with HPV L1-expressing plasmid DNA have been shown to develop specific anti-L1 antibodies. However, the route of administration seems to be important for the generation of mucosal immunity. Schreckenberger et al. reported that vaginal immunization of rabbits with HPV 6bL1 DNA induced 6bL1 virus-like particle-specific IgA antibodies in vaginal secretions and no mucosal immune response was detected in vaginal secretions of rabbits immunized intramuscularly or intrarectally (103).

The L1-specific humoral immune responses generated by L1 DNA vaccines have led to preventive effects in some animal models. For example, subcutaneous (104) or intramuscular (105) vaccination of rabbits with the L1 gene of cottontail rabbit papillomavirus (CRPV) generates antibodies capable of protecting all vaccinated rabbits (compared to no vaccination control group animals) against CRPV challenge. In another study, Stanley et al. immunized beagle dogs via particle-mediated DNA delivery (PMDD) of a plasmid encoding the canine oral papillomavirus (COPV) L1 gene to cutaneous and oral mucosal sites (106). Immunized animals developed a moderate L1 serum antibody response, and while five of six animals in the control group developed COPV papillomas, all animals vaccinated with the COPV L1 gene were protected against disease. Thus, studies in animal models elucidate the usefulness of L1-encoding DNA for generating L1-specific antibody responses that may contribute to protection from the formation of papillomas or tumors.

Although prophylactic vaccines have elicited protective immune responses in various models, several issues remain to be addressed. It is unclear whether sexual transmission is due to free viral particles or to particles still enclosed in detached squamous cells that might protect that virus from neutralizing antibody. Furthermore, the frequent and intimate nature of sexual contact implies a potentially large HPV inoculum, allowing for the potential breakthrough infection that escapes antibody-mediated neutralization. On the basis of observations made in both humans and mammals, it appears that HPV-specific antibodies are insufficient for clearing preexisting papillomavirus infection. Although HPV L1 vaccines has been shown to generate L1-specific CD8$^+$ T cell immune responses (107, 108), it is expected that such immunization
will be unable to generate significant therapeutic effects for established or breakthrough HPV infections that have escaped antibody-mediated neutralization. This is probably because capsid genes are only expressed upon terminal differentiation in the upper strata of the epidermis, but not in basal keratinocytes. In addition, cells with HPV integration usually exhibit deletion of L1, rendering these cells ineffective as a target for HPV L1-specific CD8+ T cells. Pre-existing HPV infection is highly prevalent and responsible for considerable morbidity and mortality. Evidence suggests that cellular immunity, particularly antigen-specific T cell-mediated immunity, is required for treatment of established HPV infection (39). It is therefore important to develop vaccines that induce cell-mediated immune responses specific for early viral proteins in order to effect regression of established lesions and malignant tumors.

3.4. Therapeutic HPV DNA Vaccines

Therapeutic vaccines induce specific cell-mediated immunity, which can hinder the development of pre-existing lesions and malignant tumors, and even eliminate them. Theoretically, cell-mediated immunity can directly target HPV viral products, HPV-induced cellular products, or a combination of both. Since little is known about which cellular products can serve as targets for specific cell-mediated immune responses and there is also a concern for autoimmune responses, most of the experimental vaccination systems use carcinoma-associated HPV proteins, particularly E6 and E7, as targets for specific cellular immunity.

E6 and E7 are consistently expressed in most cervical cancers and their precursor lesions but absent from normal tissues. Thus, these viral oncoproteins represent promising targets for the development of antigen-specific vaccines to treat HPV associated cervical malignancies and their precursor lesions. While many tumor-specific antigens are derived from normal or mutated proteins, E6 and E7 are completely foreign viral proteins, and may therefore harbor high antigenic peptides/epitopes that are not present in the mutant cellular protein. Furthermore, since E6 and E7 are required for the induction and maintenance of the malignant phenotype of cancer cells (24), cervical cancer cells are unlikely to evade an immune response through antigen loss. Finally, studies in animal models suggest that vaccination targeting papillomavirus early proteins such as E7 can generate therapeutic as well as protective effects (25). Although E5- and L1-specific immune responses have been observed in certain HPV vaccine studies (107, 25), it is believed that the effectiveness of such strategies against HPV are limited since these proteins are frequently deleted in cervical neoplasia and carcinoma. Therefore, E6 and E7 proteins represent the most useful targets for developing antigen-specific immunotherapies or vaccines for cervical cancer.

Researchers typically focus on vaccines targeting E7 since it is more abundantly expressed and better characterized immunologically. Furthermore, its sequence is more conserved than that of the E6 gene (26). Recently, naked DNA vaccines have emerged as important therapeutic HPV vaccines because of their stability. DNA vaccines allow for sustained expression of antigen on MHC-peptide complexes compared to peptide or protein vaccines. Furthermore, the MHC restriction of peptide-based vaccines may be bypassed with approaches that directly transduce DNA coding for antigen to APCs so that synthesized peptides can be presented by the patient’s own HLA molecules. Since DNA vaccines targeting different HPV types can be administered together, DNA vaccines may be effective for treating a variety of HPV-associated infections and tumors. These advantages have spurred interest in the development of DNA vaccines to treat cancers. DNA vaccines can be administered to the host by intramuscular injection, intradermal injection via hypodermic needle or gene gun (a ballistic device for delivering DNA-coated gold particles into the epidermis), intravenous injection, intranasal delivery or biojector delivery (for review see (70, 72)). Thus, in the current review, we will focus on therapeutic HPV DNA vaccines.

3.4.1. DNA Vaccines and Activation of T Cells

Studies have investigated the mechanisms involved with intramuscular injection or gene gun delivery of DNA vaccines. Following intramuscular injection, myocytes can uptake DNA, allowing them to produce protein and transfer antigen to bone marrow-derived professional APCs (110). Cross priming, the processing of exogenous antigen transferred from another cell (i.e. secreted from DCs or in apoptotic bodies) via the MHC class I pathway (111, 112), provides an explanation for the transfer of antigen from cells initially transfected by intramuscular immunization (i.e. myocytes) to professional APCs.

After gene gun delivery, epidermal Langerhans cells uptake DNA and function as APCs. DCs in the skin carry antigen from the skin to the draining lymph nodes, where the antigen-loaded DCs activate naïve T cells (84). Intradermal vaccination with DNA facilitates direct priming, whereby antigen expressed in DCs is directly processed within the cell and presented on MHC class I molecules to CD8+ T cells. (113). The method of DNA inoculation (gene gun versus intramuscular injection) and the form of the DNA-expressed antigen (cytoplasmic versus secreted) can also influence the type of T cell help (Th1 or Th2)(for review see (114)).

3.4.2. Intracellular Targeting Strategies to Enhance MHC class I-restricted CD8+ and MHC class II-restricted CD4+ T Cell Responses

The delivery of DNA vaccines intradermally via gene gun allows for direct targeting of genes of interest into professional APCs in vivo. Gene gun immunization has been used to test several intracellular targeting strategies that enhance MHC class I and/or class II presentation of antigen. For example, MHC class I presentation of HPV-16 E7 can be significantly enhanced by linkage of these molecules to E7 results in augmentation of
Figure 2. Strategies for Optimizing DNA Vaccines. Various strategies for enhancing the potency of DNA vaccines are currently under investigation. This figure summarizes popular sequences included in the genes insert to ensure DNA vaccine optimization.

the E7-specific CD8\(^+\) T cell immune response in vaccinated mice. Furthermore, the use of DNA encoding a signal sequence linked to E7 and the sorting signal of the lysosome-associated membrane protein (LAMP-1) to create the Sig/E7/LAMP-1 chimera can enhance MHC class II antigen processing (118). Expression of this DNA vaccine \textit{in vitro} and \textit{in vivo} targets E7 to endosomal and lysosomal compartments and enhances MHC class II presentation to CD4\(^+\) T cells compared to DNA encoding wild-type E7 (119). While chimeric E7/HSP70, ETA(dII)/E7 or CRT/E7 DNA generates potent CD8\(^+\) T cell responses through enhanced MHC class I presentation, other constructs that target antigen to MHC class II presentation pathways may provide enhanced CD4\(^+\) T cell responses. This realization raises the notion of co-administration of vaccines such as E7/HSP70 and Sig/E7/LAMP-1 in a synergistic fashion. Such an approach may directly enhance both MHC class I and class II presentation of E7 and lead to significantly enhanced E7-specific CD4\(^+\) and CD8\(^+\) T cell responses and potent antitumor effects.

Although DNA vaccines employing intracellular targeting strategies can significantly enhance MHC class I and class II presentation of antigen in transfected DCs, they may only generate a limited number of antigen-expressing DCs since naked DNA vaccines lack the intrinsic ability to amplify and spread \textit{in vivo}. This significantly limits the potency of DNA vaccines. Therefore, a strategy that facilitates the spread of antigen to more DCs may significantly enhance the potency of naked DNA vaccines.

3.4.3. Intercellular Spreading to Enhance DNA Vaccine Potency

The potency of DNA vaccines may be enhanced through the use of herpes simplex virus (HSV-1) VP22, an HSV-1 tegument protein capable of intercellular transport and useful in spreading protein to surrounding cells (120). HSV-1 VP22 (HVP22) is capable of enhancing intercellular spreading of the linked protein. Furthermore, mice vaccinated with HVP22/E7 DNA generate a significantly greater number of E7 specific CD8\(^+\) T cell precursors (117, 121, 122) and a stronger antitumor effect than wild-type E7 DNA (117). The success of the chimeric HSV-1 VP22/E7 DNA vaccine warrants the consideration of other proteins with similar trafficking properties.

At least two other proteins with purported intercellular spreading properties have been reported, including bovine herpesvirus VP22 (BVP22) (123) and Marek’s disease virus VP22 (MVP22) (124), both of which are VP22 homologues. Bovine herpesvirus VP22 shares about 22% amino acid identity to human herpesvirus VP22 (123). A previous study found that BVP22 trafficking may be more efficient than human VP22 trafficking after endogenous synthesis (123). Marek’s disease virus VP22 (MVP22) shares about 17% amino acid identity to human herpesvirus VP22 and may be capable of intercellular transport after exogenous application (125). The linkage of MVP22 to HPV-16 E7 in a context of DNA vaccine is capable of generating a significantly greater number of E7 specific CD8\(^+\) T cell precursors and a stronger antitumor
HPV DNA vaccines

effect than wild-type E7 DNA in vaccinated mice (126). Since different degrees of intercellular spreading of linked antigen encoded by DNA vaccine may influence the generation of antigen-specific immunity and antitumor effects in vaccinated mice, a head-to-head comparison of VP22 molecules may elucidate their relative ability to generate intercellular spreading of linked antigen and to influence vaccine potency. This strategy may also be combined with intracellular targeting strategies, such as HSP70, to generate even greater enhancement of antigen-specific immunity and antitumor effects.

3.4.4. Prolonging DC Survival to Enhance Immune Responses to DNA Vaccines

Although E7-specific T cell-mediated immune responses and antitumor effects can be enhanced by the vaccine strategies mentioned in Section 3.4.2 and 3.4.3, vaccine efficiency may be limited since transduced dendritic cells may themselves become targets of effector cells through apoptosis via perforin/granzyme B or death receptor pathways. One potential strategy to overcome this problem is to utilize DNA encoding inhibitors of apoptosis delivered to DCs in order to enhance the survival of DCs and prolong their ability to present the antigen of interest. Kim et al. have tested a variety of anti-apoptotic factors for their ability to enhance DC survival and E7-specific CD8+ T cell immune responses including bclXL and bcl2, members of the bcl2 family of proteins; X-linked inhibitor of apoptosis protein (XIAP); and dominant negative mutants (dn) of caspases such as dn caspase-9 and dn caspase-8, which lack key functional components and serve as inhibitors of apoptosis (Kim, personal communication). An examination of E7-specific immune responses, the antitumor effect, and the characteristics and kinetics of dendritic cell involvement, revealed that co-administration of E7-containing DNA with DNA encoding anti-apoptotic proteins enhanced DNA vaccine potency and efficacy. In addition, the anti-apoptotic strategy may be used in conjunction with other intracellular targeting strategies or intercellular spreading strategies to generate synergistic effects in enhancing DNA vaccine potency (Kim et al., unpublished observations).

3.4.5. Improving DNA Vaccine Potency with Cytokines and Costimulatory Adjuvants

It is well-known that costimulators are required to generate a CTL response. Methods that employ cytokines or costimulatory molecules may enhance the potency of DNA vaccines (82, 127, 128). Leachman et al. demonstrated that priming the E6 DNA vaccination site with a GM-CSF-expressing vector greatly enhances the effects of cottontail rabbit papillomavirus (CRPV) E6 vaccination, increasing tumor regression frequency and probability of rabbits remaining disease free after CRPV challenge (99). Tan et al. have shown that administration of IL-12 at the vaccination site of gene gun-administered plasmid DNA encoding E7 increased vaccine induced therapeutic efficacy (129). Thus, cytokines and costimulatory molecules may act as useful adjuvants for HPV DNA vaccines.

3.4.6. Improving DNA Vaccine Potency by Enhancing Protein Degradation

The immune response elicited by DNA vaccines may be augmented by manipulating pathways for intercellular protein degradation. Ubiquitin, a small protein cofactor, targets conjugated protein for recognition and degradation within the proteasome. Velders et al. have shown that a multi-epitope vaccine for HPV protected 100% of vaccinated mice against challenge with tumor cell line expressing HPV 16 E7, when ubiquitin and certain flanking sequences were included in the gene insert (130). Similarly, Liu et al. observed enhancement of E7-specific CTL activity and protection against E7-expressing tumors in mice given a DNA vaccine with a ubiquitinated L1-E7 gene insert (131). Although ubiquitin may be a useful molecule for expediting protein degradation and antigen processing, it is not the only means of enhancing intercellular protein degradation. Shi et al. engineered mutations into two zinc-binding motifs of an HPV-16 E7 DNA vaccine to generate a rapidly degraded E7 protein (132). This mutated E7 protein elicited a significantly enhanced E7-specific CTL response and better protection compared to a wild type E7 DNA vaccine (132). These studies suggest that the enhancement of intercellular degradation of the antigen of interest may increase the immunogenicity of DNA vaccines.

3.4.7. Safety of DNA Vaccines

Although the efficacy of DNA vaccination is important, safety is also a critical issue. DNA present in the vaccine may integrate into the host genome, potentially inactivating tumor suppressor genes or activating oncogenes, thereby inducing malignant transformation of the host cell. Fortunately, it is estimated that the frequency of integration is much lower than that of spontaneous mutation and integration should not pose any real risk (133). A second issue concerns potential risks associated with the presence of HPV-16 E7 protein in host cells. E7 is an oncoprotein that disrupts cell cycle regulation by binding to pRb, a tumor suppressor protein in nuclei (134). The presence of E7 in the nuclei may lead to accumulation of genetic aberrations and eventual malignant transformation of the host cells. To avoid such problems, strategies such as the endosomal/lysosomal-targeting Sig/E7/LAMP-1 DNA vaccine may be employed to divert E7 away from the nucleus to regions such as the endosomal and lysosomal compartments to physically separate E7 from pRb. In addition, detailed mutational analysis of E7 has led to the identification of a number of mutations that abrogate the transformation activity of E7 (135-138). One recent study demonstrated that a DNA vaccine encoding E7 with a mutation which inactivate Rb-binding site was able to enhance CTL activity and E7-specific antitumor effects compared to wild-type E7 (132). DNA vaccines using a shuffled E7 gene may also alleviate concerns of oncogenicity associated with E7 (121). Another strategy to avoid the problem of the oncogenicity of E7 is to use a DNA vaccine encoding a string of multiple epitopes flanked by defined spacer sequences; this may be safe and promising for tumor protection and therapy, particularly if epitopes are targeted to the protein degradation pathway (130). Ultimately, DNA vectors employed in human
HPV DNA vaccines

clinical trials may use a minimally mutated E7 gene or multiepitope gene approach in which critical epitopes are preserved while potential oncogenic activity is eliminated.

4. PERSPECTIVE

Recently, significant progress has been made in the field of HPV naked DNA vaccine development. The determination that HPV is an etiological agent for cervical cancer and its precursor lesions has paved the way for the development of preventive and therapeutic HPV vaccines that may lead to the control of HPV-associated malignancies and its potentially lethal consequences. An understanding of the molecular progression of cervical cancer has led to the realization that HPV L1 and L2 are suitable targets for preventive vaccines, while E6 and E7 are important targets for the development of HPV therapeutic vaccines for the control of established HPV infections and HPV-associated lesions. The emergence of DNA vaccines and various strategies to engineer potent anti-HPV immune responses represents an important advance in cervical cancer immunotherapy. Early clinical application of DNA vaccines against HPV is underway, and may pave the way for more advanced clinical investigation. Clinical HPV vaccine trials provide a unique opportunity to identify the characteristics and mechanisms of the immune response that best correlate with clinical vaccine potency. Such immunological parameters will help define protective immune mechanisms for controlling HPV infections and HPV-related disease. Comprehensive information on these protective immune mechanisms in humans will facilitate the development of more effective anti-HPV DNA vaccines to fight cervical cancer.

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HPV DNA vaccines


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