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Review Paper

Breaking Barriers: Recent Innovations in Cancer Vaccine Development

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Cancer is one of the major problems for health workers and Researchers worldwide. Scientists and health workers use various types of procedures to cure and diagnose cancer. Somehow these procedures provide significant outcomes but not the complete elimination of cancer. Hence researchers around the globe are looking for novel and more efficient techniques. Among these recent advances cancer vaccine is one of the highlighted procedures, and hope for future cancer treatment. The current review was carried out to examine the cancer vaccine's current status. From the investigation and overview, we found that only a few vaccines are in clinics against different types of cancer among these humans Papillomavirus Vaccine and HBV vaccines are more common. Although the vaccine search against cancer is still in progress, it will soon come to clinics.

Abstract

Introduction

The global health community faces cancer as one of its most critical challenges because it affects millions of people throughout the world. The worldwide incidence of new cancer cases reached more than 20 million in 2024 while cancer deaths numbered about 10 million according to Bray et al. (2024) and WHO (2024). Treatment outcomes with conventional methods such as chemotherapy and radiotherapy and surgery remain poor because therapy resistance leads to metastasis and recurrence (Stoop et al., 2024). Scientific researchers dedicate their efforts to finding better cancer treatment strategies because of the ongoing high mortality rates (Ringborg et al., 2024). The scientific field of molecular biology together with genomics and immunotherapy has produced recent discoveries which now provide new cancer treatment methods (Zafar et al., 2024; Arjmand et al., 2024; Jonas and McManamon, 2024; Rehman et al., 2025). Cancer vaccines have emerged as promising cancer treatment options that can deliver precise and sustained immune-mediated tumor elimination (López-Estévez et al., 2024). The study of cancer immunoediting provides essential knowledge for developing vaccines because it describes the ongoing process of cancer cell interactions with the immune system (Zingoni et al., 2024). Scientific investigations currently focus on improving tumor-specific immune responses to create advanced immunotherapies (Lu et al., 2024). Cancer treatment has experienced a revolutionary change through immunotherapy which includes three major therapeutic methods: immune checkpoint inhibitors (ICIs) and chimeric antigen receptor (CAR) T-cell therapy as well as oncolytic viruses (Kamrani et al., 2024). Since ipilimumab received FDA approval as the first immunotherapy in 2011 the field has experienced major advancements (Stenger and Miller, 2024) (Figure 1). ICIs have shown limited effectiveness in clinical trials because durable responses occurred in only 12% of cancer patients so better treatments remain necessary (Sala et al., 2024; Almawash, 2025). The scientific community investigates cancer vaccines as a solution to enhance anti-tumor immunity by priming and boosting immune responses (Goyal et al., 2024). Cancer vaccines function differently from standard infection-preventing vaccines since they educate the immune system to detect and destroy cancerous cells (Mohite et al., 2024; Adedokun et al., 2025). The following review offers an updated evaluation of cancer vaccines along with their present clinical developments and their potential future applications in oncology.

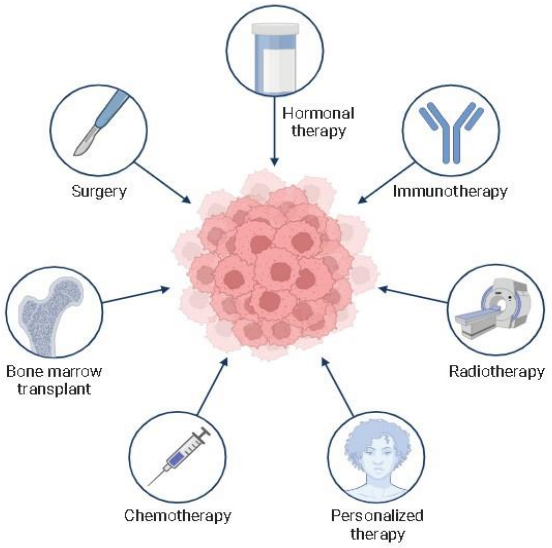

Figure 1. The treatment of cancer using different strategies. Among these immunotherapies, surgery, radio therapy is more common. The advancement in molecular biology now makes it easier for researcher to create cancer vaccine.

Cancer Vaccines

The immune system receives activation from biological vaccine preparations that fight against infectious agents. Research has allowed scientists to develop multiple successful vaccines for dangerous diseases throughout the years (Goetz et al., 2024). The global health burden of cancer continues to exist so new therapeutic methods are needed to combat this disease. The innovative approach of cancer vaccines provides patients with hopeful prospects for millions of individuals (Goyal et al., 2024). New developments in vaccine technology have expanded their applications because circRNA vaccines and nucleic acid-based vaccines (mRNA/DNA) and peptide-based vaccines and DNA-nanostructured vaccines demonstrate significant potential according to Chen et al. (2024), Smith and Zhang, (2024), Gomari et al. (2025), Babiker et al. (2025) and Fournier et al. (2025). CircRNA vaccines deploy stable circular RNA molecules to express tumor-specific antigens which produce powerful and extended immune reactions (Li et al., 2024; Bu et al., 2025). The rapid development along with high tumor antigen delivery efficacy of mRNA vaccines (similar to COVID-19 vaccines) has made them widely popular for cancer therapy (Wei et al., 2024).

The synthetic tumor peptides used in peptide-based vaccines activate cytotoxic T-cells precisely while producing minimal side effects (Park et al., 2024). DNA-nanostructured vaccines employ engineered nanocarriers as carriers to improve antigen presentation and immune activation which enhances both vaccine stability and delivery (Zhao et al., 2024). Preventive cancer vaccines have limited approval for clinical use because they primarily target viruses that cause cancer development. These include: The HPV vaccine prevents cancers of the cervix, vagina, anus and vulva (Dash et al., 2024). The HBV vaccine protects against hepatitis B virus and simultaneously decreases the risk of liver cancer (Wei et al., 2024). The development of therapeutic cancer vaccines now targets patients who have already developed cancer. The therapeutic vaccines operate as immunotherapies to educate the immune system about cancer cell detection and destruction (Goyal et al., 2024; Bergman, 2024; Sarangi et al., 2025) (Figure 2).

The vaccines work by targeting cancer-specific antigens that remain in the body after tumor removal to stop cancer from returning (Yang et al., 2024). The FDA has approved Sipuleucel-T as a personalized vaccine for treating metastatic prostate cancer (Capuozzo et al., 2024) (Table 1). The treatment process involves obtaining a patient's white blood cells to modify them with prostate cancer antigens outside the body before returning them to stimulate anti-tumor activity. The BCG vaccine (Bacillus Calmette-Guérin) functions as bladder cancer immunotherapy through bacterial components to activate immune responses against tumor cells (Arjmand et al., 2024).

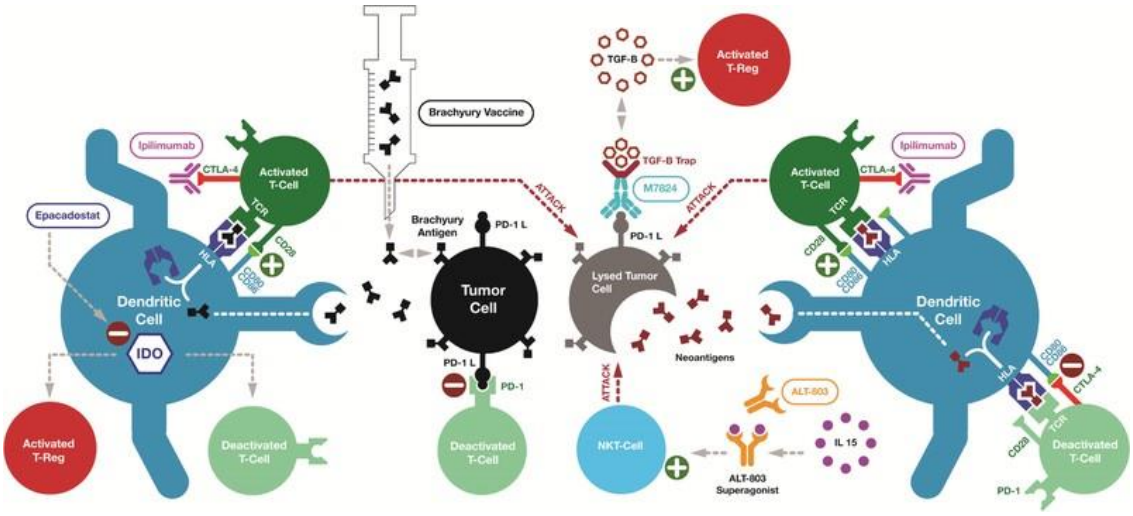

Figure 2. This diagram captures the synergistic interaction between different immunotherapy modalities to combat cancer, highlighting how each approach contributes to enhancing the immune system's ability to recognize and eliminate cancer cells. Courtesy of Z. Folzenlogen, MD, Denver, CO.

Recent Innovations in Cancer Vaccine Development

Types of cancer vaccines

Researcher investigating different types of cancer vaccine and the working mechanism of these vaccine (Sayour et al., 2024). More research are needed on these vaccine, how these vaccine will be efficient against which type of cancer and how it will be work. Currently the cancer vaccine that are under investigation including: protein or peptide vaccine, these vaccines are made from special protein found in cancer cells or small portions of protein called peptides (Katsikis et al., 2024). DNA/RNA cancer vaccine, this vaccine is synthesized from small portion of DNA or RNA found in cancer cells (Sarangi et al., 2024). Whole cell vaccine, synthesized from whole cancer cells. Due to advancement in sequencing technology, now the scientists are able to study the genomics of cancer cells and design vaccine, which are administrated to the body to beat cancer. Scientist taking cancer cells from patient manipulate it and inject it to the patients, by this way immunity developed against cancer cells (Yang et al., 2024). Dendritic cells vaccine, these vaccines help the body to eliminate abnormal cells. Scientist developing dendritic cell in lab and used it against cancer cells (Qian et al., 2024). Viral vaccine, these vaccines are manufactured from virus which are genetically modified. These viral vectors are administrated to body where immune system recognize it and produced antigen against cancer cells (Janes et al., 2024). Imlygic a treatment also called T-VEC (talimogene laherparepvec) is similar to virus vaccine, use a strain of the cold sore virus (Herpes simplex virus). The virus is genetically modified; therefore, the virus modified the immunity to destroy cancer cells and ignore healthy cells (Saboowala, 2024). This treatment is approved and used against melanoma skin cancer (Figure 3). This vaccine is also in trails for treatment of head and neck cancer. Types of cancer vaccine are:

Protective vaccine against cancer

These vaccines are the more conventional types of cancer vaccine, they enhance the immunity to protect the body from foreign particles (Chandarana, Tiwari, 2024). Example of these vaccine are flu shot, COVID-19 and measles. This vaccine is also helpful against cancer, protect the body from viral infection which may cause cancer. Currently the approved protective vaccine are HPV and HBV, these vaccines are used against different types of cancer (Chandarana, Tiwari, 2024).

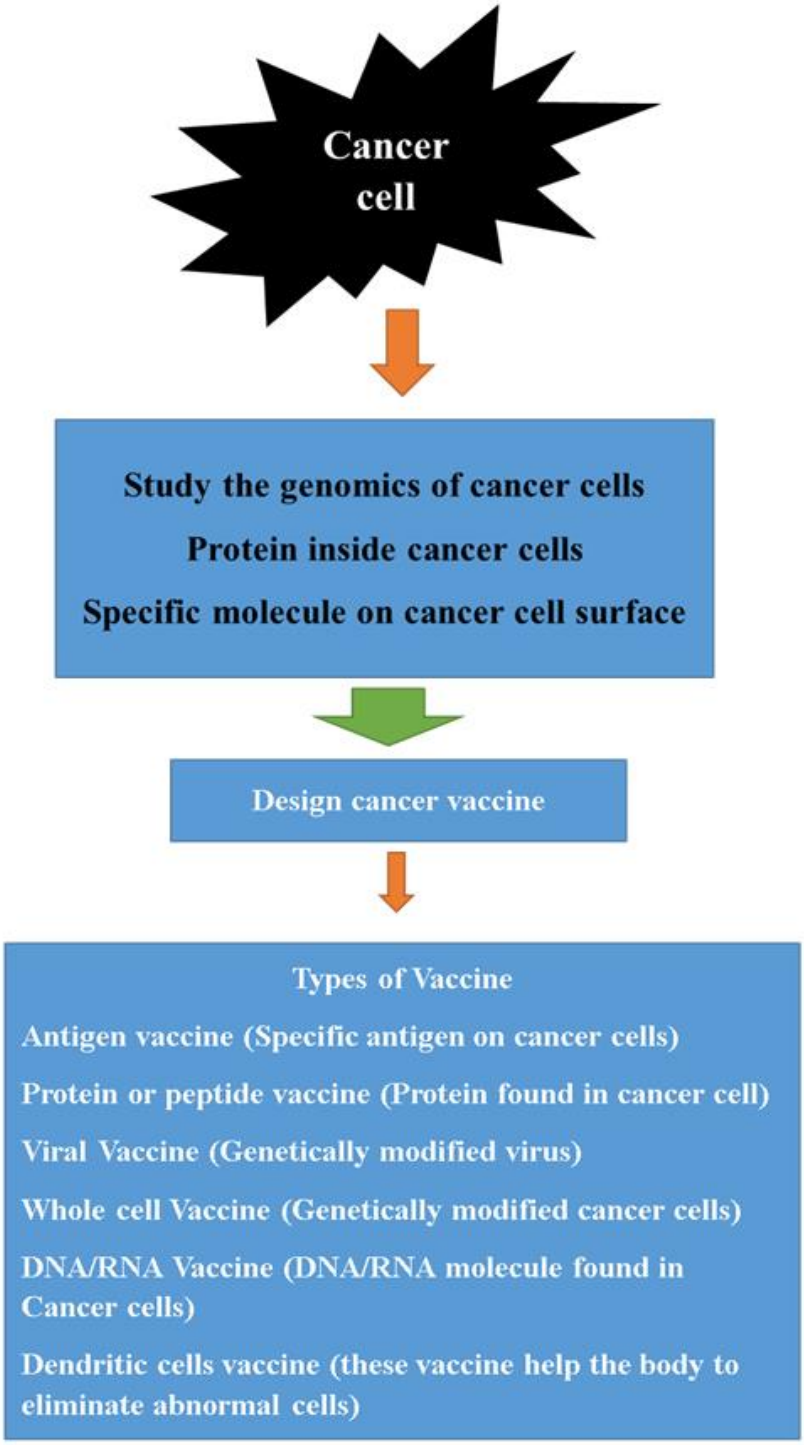

Figure 3. The development of cancer vaccine. Cancer genomic, proteomic and antigen on the surface of cancer cell are isolated and vaccine are designing in lab against these cancer cells to enhance the body immunity and remove the cancer completely.

Cancer therapeutic vaccine

The cancer therapeutic vaccine basically synthesis from antigen of a specific antigen on cancer cells. These vaccines guide the immunity to recognize the cancer cell and destroy it (Kenoosh et al., 2024). Mostly these vaccines are used after therapy, which enhance the immunity against the remaining cancer cells (Kenoosh et al., 2024). Although cancer therapeutic vaccines have some limitation, like some time it switch on the immunity against cancer cells, but the cells cannot entre to the tumor (Han et al., 2024). Or if they enter the cancer cell shown itself like healthy cells. Therefore, due to this challenge it makes the hard time for immunity to find cancer cells (Han et al., 2024). The other major issue is to find specific cancer cells antigen, because some time it is found in both healthy and cancer cells. Therefore, immunity destroy healthy cells, this is unwanted side effect of cancer therapeutic vaccine. Other problems including size of tumor (large tumor contain more immune suppressive cells). To reduce these side effect this vaccine is administered with other drugs in combination (Han et al., 2024). Age and weakened immunity is also major issues in using cancer therapeutic vaccine (Wu et al., 2024). Hence, we concluded that more studies and research are needed to increase the efficiency of these vaccine. May be in future the scientist reduced these obstacles and vaccine will be available for every one and we will save millions of lives.

Table 1. FDA-Approved Therapeutic Cancer Vaccines

Serial No.	Cancer Type	Vaccine Name	Mechanism of Action	Approval Year
1	Prostate Cancer	Sipuleucel-T (Provenge®)	Autologous cellular immunotherapy: Patient's immune cells are harvested, activated with a prostate cancer antigen (PAP-GM-CSF), and reinfused to stimulate an anti-tumor immune response. Extends survival in metastatic prostate cancer.	2010
2	Bladder Cancer	Bacillus Calmette-Guérin (BCG)	Live attenuated bacterium (Mycobacterium bovis) delivered intravesically to trigger a localized immune response against non-muscle-invasive bladder cancer (NMIBC).	1990
3	Bladder Cancer	Nadofaragene firadenovec (Adstiladrin®)	Non-replicating adenoviral vector delivering interferon alfa-2b gene to enhance immune recognition of tumor cells in BCG-unresponsive NMIBC. Administered intravesically.	2022
4	Melanoma	Talimogene laherparepvec (T-VEC, Imlygic®)	Genetically modified oncolytic herpesvirus (HSV-1) that selectively replicates in tumor cells, lysing them and releasing tumor-	2015

			associated antigens to stimulate systemic immunity. Used for unresectable metastatic melanoma.	
5	Melanoma	Lifileucel (Amtagvi™)	First FDA-approved tumor-infiltrating lymphocyte (TIL) therapy for advanced melanoma. Autologous TILs are expanded ex vivo and reinfused to target tumor-specific antigens.	2024
6	Bladder Cancer	Anktiva (N-803, Nogapendekin alfa inbakicept)	IL-15 superagonist combined with BCG to enhance T-cell and NK-cell activity in BCG-unresponsive NMIBC. Administered intravesically.	2023

Vaccines and clinical trials

Clinical trials are key to learning more about both cancer prevention vaccines and cancer treatment vaccines. Researchers are testing vaccines for many types of cancer (Table 2).

Table 2. Cancer Vaccines under Clinical Trials

Serial No.	Vaccine Name/Type	Target Cancer	Mechanism & Clinical Trial Phase	Developer/Institution
1	**HER2-targeted viral vaccine** + BCG	Bladder cancer (NMIBC)	Modified virus delivers HER2 antigen to enhance immune recognition. Compared against standard BCG therapy (Phase II).	Multiple centers
2	**mRNA-4157 (V940)** + Pembrolizumab	Melanoma, NSCLC, RCC	Personalised neoantigen mRNA vaccine combined with anti-PD-1 (Phase III).	Moderna/MSD
3	**GNOS-PV02** (DNA plasmid vaccine)	Hepatocellular carcinoma	Targets tumor-specific neoantigens via electroporation (Phase II).	Geneos Therapeutics
4	**PGV-001** (Personalised peptide)	Solid tumors (e.g., GBM, ovarian)	Customized multi-peptide vaccine targeting patient-specific mutations (Phase I).	Mount Sinai
5	**ELI-002** (Amphiphile peptide)	Pancreatic/Colorectal (KRAS-mutated)	Targets KRAS G12D/G12R	Elicio Therapeutics

Recent Innovations in Cancer Vaccine Development

Serial No.	Vaccine Name/Type	Target Cancer	Mechanism & Clinical Trial Phase	Developer/Institution
			mutations with CpG adjuvant (Phase II).	
6	**GRT-C901/GRT-R902** (mRNA)	Colorectal, pancreatic	Shared neoantigen vaccine + checkpoint inhibitors (Phase I/II).	Gritstone Bio
7	**BNT122 (RO7198457)** (mRNA)	Melanoma, NSCLC	Patient-specific neoantigen vaccine (Phase II).	BioNTech/Genentech
8	**GVAX Pancreas** (Whole-cell)	Pancreatic cancer	GM-CSF-secreting allogeneic tumor cells to stimulate immunity (Phase II).	Aduro Biotech
9	**NEO-PV-01** (Neoantigen peptide)	Melanoma, bladder	Synthetic long peptides targeting tumor mutations (Phase II).	Neon Therapeutics
10	**VTP-850** (Prostate GVAX)	Prostate cancer	Whole-cell vaccine with anti-CTLA-4 (Phase II).	Janssen
11	**DSP-7888** (WT1 peptide)	Glioblastoma, AML	WT1-targeting vaccine + immune adjuvants (Phase III).	Boston Immunotherapeutics
12	**VBI-1901** (CMV gB vaccine)	Glioblastoma	Targets cytomegalovirus antigens in tumors (Phase II).	VBI Vaccines

Recent advancement in Cancer vaccine

Recently NHS England use personalized vaccine against bowel cancer in patients, the clinical trials were performed on thousand cancer patients. The vaccine was used for different types of cancers. 36 patients with HCC were administrated with personalized anti-tumor vaccine to PD-1 inhibitor therapy. There was no adverse effect observed, except of mild injection site reaction. About 8% of patients showed no evidence of tumor after combined therapy (personalized anti-tumor vaccine and PD-1) (NHS England, 2024). In another study performed at university of Florida using mRNA

cancer vaccine showed quick response of immunity against glioblastoma (UF Health, Cancer center, 2024). Currently in this study we investigated type five cancer vaccine that are under study (Table 3). Hopefully very soon it will be available. Currently several cancer vaccines are in clinical trials with significant outcomes. These vaccines are design to guide patients' immunity against cancer cells. The advances in genomic medicine and molecular medicine make easier to create more precise and effective cancer vaccine (BioSpace 2024). The most recent advances in cancer vaccine are described here, five major research in cancer vaccine are:

Table 3. Detail of top five cancer vaccine.

Vaccine name	Type of cancer	Mechanism	Results of trails
Moderna and Merck's Melanoma Vaccine	Melanoma	Moderna and Merck's mRNA-based vaccine for the adjuvant treatment of patients with resected high-risk (stage IIB-IV) melanoma.	In July, the partners announced a Phase III trial for the vaccine, dubbed V940/mRNA-4157, which will be delivered alongside the immune checkpoint inhibitor Keytruda (pembrolizumab). This announcement was made following the release of positive Phase IIb results in April that showed patients treated with V940/mRNA-4157 plus Keytruda had a 44% lower risk of cancer recurrence or death than patients treated with Keytruda alone.
BioNTech's Pancreatic Cancer Vaccine	Pancreatic Cancer	Autogene cevumeran, an mRNA vaccine against pancreatic ductal adrenal cancer (PDAC), had been treated. consists of an mRNA encoding for up to 20 neoantigens tailor-made for different patients, is delivered alongside the immune checkpoint inhibitor atezolizumab.	The vaccine, jointly developed by BioNTech and Genentech, was previously tested against a host of solid tumors in a Phase I trial where it triggered a large cohort of neoantigen-specific T cells in PDAC patients, many of whom went for long periods without cancer recurrence. This is particularly important for PDAC, which has a high relapse rate and is notoriously difficult to treat. The Phase II trial will recruit 206 patients and is expected to be completed in 2029.

Recent Innovations in Cancer Vaccine Development

Vaccine name	Type of cancer	Mechanism	Results of trails
Transgene's Viral Vector-Based Vaccine	ovarian cancer, head and neck cancer	The vaccine, is use for the treatment of ovarian cancer and HPV-negative head and neck cancer, has shown robust immune responses in patients.	The vaccine, which is currently in Phase I trials for ovarian cancer and HPV-negative head and neck cancer, has shown robust immune responses in patients. The ability to generate a strong immune response, especially in cancer patients who may already have weakened immune systems, is the first indicator that a cancer vaccine can be effective.
OSE's Advanced NSCLC Vaccine	lung cancer	Its cancer vaccine for advanced non-small cell lung cancer (NSCLC).	In September, OSE Immunotherapeutics published positive results from a Phase III trial
Nykode's Cervical Cancer Candidate	Cervical Cancer	The vaccine, VB10.16, was delivered to 52 trial participants in combination with atezolizumab. Patients who received the vaccine were tracked for one year and showed a median overall survival of 16.9 months.	Norway–based Nykode Therapeutics in April announced positive results for the Phase IIa trial of its cervical cancer vaccine.

Summary

The advancement in technology, especially sin molecular biology and computer sciences have revolutionized the cancer treatment. Now the scientist are able to make vaccine against cancer and eliminate the fatal disease completely. The future is bright, millions of life will be save. However, still many challenges are a head in term of the suppression of immunity by cancer cells, size of tumor and reduced the side effect. Researcher using vaccine with other medicine to reduce the adverse effect of vaccine. Sometime the vaccine activates the immunity, but the white blood cell cannot entre to the tumors. Beside these very limited clinical trials are also one of the biggest obstacles in cancer vaccine. Although from our investigation we found that only a few vaccines are approved, and very few are under clinical trials. We need to enhance and increase the clinical

trials on large scale. For example, in NHS trails only 8% patients showed significant results out of 36 patients.

Current research and development in cancer vaccines focus on enhancing efficacy, minimizing side effects, and expanding the range of cancers they can effectively treat. While some vaccines have shown promising results in clinical trials, the field continues to evolve with ongoing efforts to improve outcomes for cancer patients. Overall, while there are challenges ahead, ongoing research and technological advancements are likely to accelerate the development and implementation of effective cancer vaccines, bringing new hope to patients and significantly improving outcomes in the fight against cancer.

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