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The role of biotechnology in reducing cancer mortality: Emerging solutions in early detection and prevention

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Abstract

Cancer remains a leading cause of death worldwide, with rising incidence and mortality rates highlighting the urgent need for innovative approaches to early detection and prevention. Traditional treatment strategies, though effective in certain cases, are limited by late-stage diagnoses and therapeutic resistance. This manuscript explores how biotechnology is being used to address these challenges, focusing on advancements made in the past decade. Key innovations include liquid biopsy, next-generation sequencing (NGS), artificial intelligence (AI) in imaging, biomarker discovery, gene editing technologies like CRISPR/Cas9, RNA-based therapeutics, immunoprevention, and chemoprevention strategies. The integration of AI and big data analytics further allows personalized cancer risk prediction and prevention strategies, which can be applied on a population level. These biotechnological advancements offer promising avenues for reducing cancer mortality by enabling earlier, more accurate detection and more effective preventive interventions. However, widespread adoption and equitable access to these technologies remain crucial. This paper calls for collaborative efforts across scientific, clinical, and policy domains to maximize the global impact of biotechnology in controlling cancer.

Keywords: Cancer Prevention; Biotechnology; Early Detection; Liquid Biopsy; Gene Editing; CRISPR-Cas9; Artificial Intelligence; Biomarkers; RNA-Based Therapeutics; Immunoprevention; Next-Generation Sequencing; Cancer Mortality; Personalized Medicine; Big Data Analytics

1. Introduction

1.1. Cancer Mortality and the Need for Innovation

Cancer remains the second leading cause of mortality worldwide. The global burden of cancer is staggering; in 2022, there were about 20 million new cancer cases, including non-melanoma skin cancers. and 9.7 million cancer-related deaths [1]. As cancer rates continue to increase, so does the urgency to develop better strategies for its detection and prevention to ensure that precious lives are not lost. Traditional methods of cancer treatment, such as surgery, chemotherapy, and radiation, have been shown to be effective in managing certain cancers. However, their impact is limited by late-stage diagnoses and the development of drug resistance [2]. As a result of this, there is a need for innovative solutions that can detect cancer at its earliest stages and prevent its occurrence altogether.

The detection of cancer early is very important for improving cancer survival rates, as it enables timely intervention and reduces the need for aggressive treatments [3]. Prevention, on the other hand, can save lives by reducing the incidence of cancer altogether before it shows up in people. Biotechnology, with its rapid developments, has emerged as a key player in these areas, offering groundbreaking solutions that promise to reshape how we approach cancer care.

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This manuscript explores the emerging biotechnological solutions in cancer early detection and prevention over the past 10 years. It will focus on the cutting-edge technologies and breakthroughs that are playing an increasingly vital role in reducing the deaths that cancer brings. By looking at the recent advancements, such as liquid biopsy, AI-based imaging, gene editing, and immune therapies, this paper aims to lay out the potential of biotechnology to revolutionize cancer care in the years to come.

2. Emerging Technologies in Cancer Early Detection

2.1. Liquid Biopsy: Revolutionizing Early Diagnosis

Liquid biopsy is a non-invasive diagnostic tool that has the potential to detect cancer at its earliest stages. Unlike traditional biopsies, which require tissue samples from tumors, liquid biopsy analyzes blood or other bodily fluids for the presence of cancer-related biomarkers, including circulating tumor DNA (ctDNA), circulating tumor cells (CTCs), and microRNAs [3]. Tissue biopsy is the main method for the diagnosis and biological analysis of various solid tumors; however, the disadvantages of this method are related to insufficient tissue specimen collection and intratumoral heterogeneity [4].

Recent developments in liquid biopsy have allowed cancers to be detected in their early stages, sometimes before symptoms even arise. This breakthrough technology allows for earlier diagnosis, which is crucial for improving survival rates. For instance, ctDNA analysis can detect specific genetic mutations that are commonly associated with certain types of cancer, including breast, lung, and colorectal cancers [5].

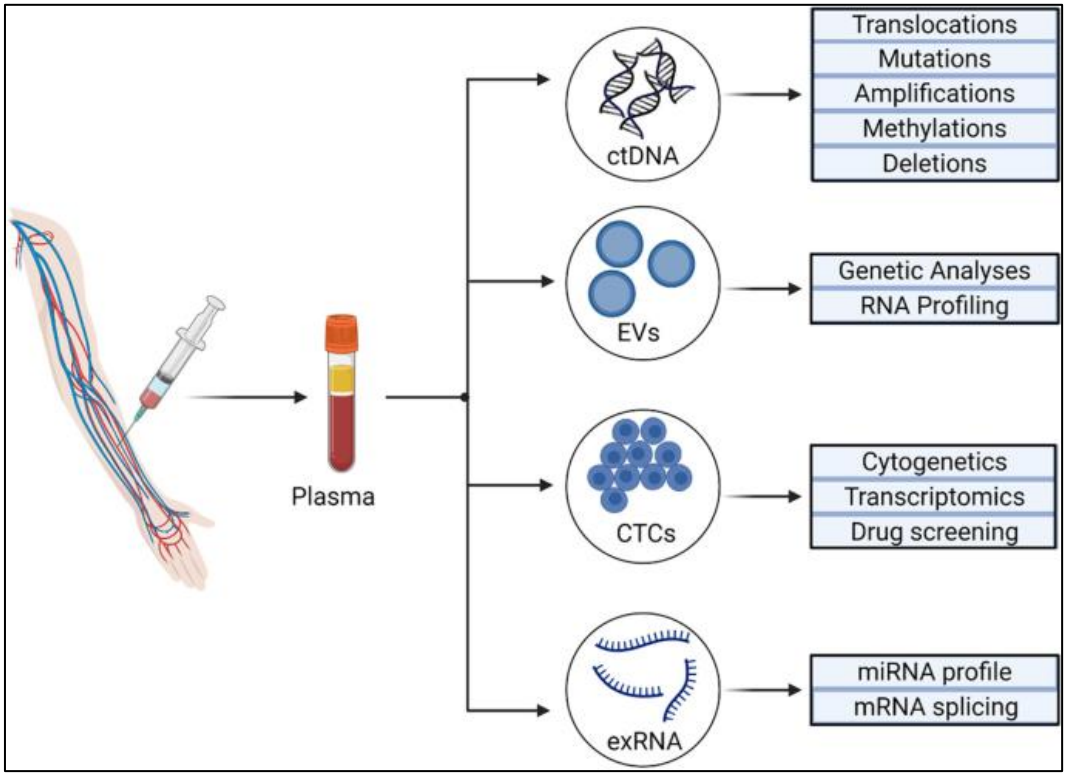

Figure 1 Candidate analytes in liquid biopsy and their possible usage in Cancer detection and prognosis [5]

Furthermore, this technology is paving the way for multi-cancer early detection panels that can simultaneously detect several types of cancers from a single blood test, significantly improving how efficient diagnostics can be.

2.2. Next-Generation Sequencing (NGS) in Early Cancer Detection

Next-generation sequencing (NGS) has become a powerful tool in the early detection of cancer. The advantage is that it allows for the deep sequencing of DNA and RNA, providing comprehensive molecular profiles of tumors. This technology aids the identification of genetic mutations, copy number variations, and epigenetic changes that may indicate the presence of cancer before it becomes clinically detectable. One of the most exciting applications of NGS in early cancer

detection is its ability to detect minimal residual disease. This is a phenomenon whereby small amounts of cancer cells remain after they have been treated [6]. NGS can identify these low levels of cancer-related mutations, potentially predicting recurrence months or even years before clinical relapse occurs. Early intervention in these cases could significantly improve patient outcomes with regard to disease progression or even mortality.

NGS is widely used across diverse applications such as whole-genome sequencing (WGS), whole-exome sequencing (WES), transcriptome sequencing, targeted region sequencing, epigenetic sequencing, and others [7]. In oncology, it has become a vital tool for exploring the genetic complexities cancer presents. Its ability to sequence whole cancer genomes allows for thorough detection of genetic mutations, structural variations, and other genomic changes that promote tumor growth [8]. This is essential for developing precision medicine approaches, allowing treatments to be tailored to the exact genetic profile of a person's tumor.

2.3. AI and Machine Learning in Diagnostic Imaging

Artificial intelligence (AI) and machine learning are changing the field of medical imaging, enhancing the early detection of cancers. AI algorithms are taught to analyze medical images such as MRI, CT scans, and mammograms [9] with greater accuracy and speed than traditional methods. These algorithms can detect tiny patterns and abnormalities that may go unnoticed by human radiologists, enabling earlier identification of tumors. For example, AI has been shown to improve the detection of breast cancer through mammography by accurately identifying malignant masses with fewer false positives and false negatives. AI has also been shown to analyze environmental and genetic factors and build models to predict the chances of individuals developing cancer [10]. This can guide lifestyle interventions, early screenings, and preventive measures. Moreover, AI is being used to add medical imaging data with genetic and clinical information, providing a more holistic picture of a patient's condition and improving diagnostic precision.

2.4. Biomarker Discovery and Advanced Diagnostic Panels

The discovery of novel biomarkers is crucial for advancing early cancer detection. A biomarker describes a broad subcategory of medical signs that are objective suggestions of a medical state that are observed from outside the patient, and can be measured accurately and reproducibly [11].

Biotechnology has enabled the identification of new biomarkers such as proteins, lipids, and small RNAs that can be detected in bodily fluids or tissue samples. These biomarkers can serve as indicators of the presence of cancer, even before tumors are large enough to be detected through traditional imaging methods [12]. Recently, we have seen significant methodological advances and a wealth of knowledge, driving progress in early cancer detection biomarker research and deepening our understanding of how it is linked to human physiology and diseases [12]. Progressions that have been made in biosensors and lab-on-a-chip technologies have also made it possible to develop point-of-care diagnostic tools for cancer. These portable, low-cost devices can detect multiple cancer biomarkers in a single test, making them highly efficient for large-scale screening and in regions with limited access to healthcare infrastructure. As these diagnostic tools become more widely available, they will play a key role in improving early detection and reducing cancer mortality rates, especially in low-resource settings.

3. Emerging Cancer Prevention Technologies

3.1. Gene Editing for Cancer Prevention: CRISPR and Beyond

Gene editing technologies, particularly CRISPR/Cas9, are bringing new possibilities to cancer prevention. CRISPR, which is a gene editing tool, allows scientists to modify the DNA of living organisms, including humans, precisely. In the context of cancer, CRISPR can be used to correct genetic mutations that predispose individuals to cancer, such as mutations in the BRCA1 and BRCA2 genes, which increase the risk of breast and ovarian cancer. CRISPR–Cas9 allows precise targeting of precise genomic locations, which enable researchers to edit both genes and the epigenetic marks that control gene activity. Epigenetic changes, which refers to a change in how genes are expressed without there being a change in a DNA sequence like DNA methylation, histone modifications, and chromatin structure alterations can show whether tumor suppressor genes are turned off or oncogenes are turned on. By accurately editing these marks, scientists can correct abnormal gene expression patterns that raise cancer risk [13,14].

Inherited epigenetic patterns may increase the risk of cancer and other genetic disorders. The potential to change these patterns offers significant promise for preventing disease. CRISPR-based epigenetic editing can be customized to an individual's specific genetic and epigenetic profile, advancing personalized medicine efforts that aim to lower disease risks before symptoms appear or tumors form. This strategy is valued for people with familial cancer syndromes that are known or inherited epigenetic irregularities [15].

A key benefit of CRISPR–Cas9 lines in its exceptional ability to be accurate. By designing guide RNAs to target specific sequences, CRISPR can selectively edit epigenetic marks at exact genomic sites, reducing off-target effects and unintended change to nearby DNA. This contributes to safer and more dependable results in potential clinical uses, and also preventing possible mutations which may come up as a result of mistaken edits [15].

CRISPR-driven epigenetic editing can create lasting, potentially heritable modifications. By reshaping the epigenetic makeup of a cell or organism, scientists can set stable gene expression patterns that endure over time and through cell divisions. When these changes occur in germline cells, the altered epigenetic marks may be inherited by future generations, possibly lowering cancer risks for their descendants [15]. Inherited epigenetic changes impact not only individuals but also entire family lineages. Modifying these marks in germ cells (sperm and eggs) offers the potential for prevention across multiple generations. Though it is highly debated, this approach could be transformative in breaking inherited cancer risk cycles, especially in families affected by conditions like Lynch syndrome or hereditary breast and ovarian cancer syndrome [15].

3.2. RNA-Based Therapeutics: A New Frontier in Cancer Prevention

RNA-based therapeutics are emerging as a powerful tool for cancer prevention. RNA interference (RNAi) and antisense oligonucleotides (ASOs) are two key technologies being explored to prevent cancer by silencing oncogenes, which are the genes that drive cancer development. Antisense oligonucleotides (ASOs) specifically bind to target RNA sequences and regulate protein production in different ways. As an emerging field in drug development, ASOs aim to address the disease at its RNA source, providing a promising alternative to treatments that target downstream processes until protein synthesis happens [16]. These therapies can be used to block the expression of specific genes that promote tumor growth, effectively preventing cancer from developing in the first place [17].

Moreover, mRNA-based vaccines, which gained widespread attention during the COVID-19 pandemic, are being explored for cancer prevention. Researchers are working on developing mRNA vaccines that target specific tumor-associated antigens, stimulating the immune system to recognize and destroy precancerous or cancerous cells. The basis for mRNA-based vaccines is in their personalization. These vaccines could provide an effective strategy for preventing cancers related to chronic viral infections, such as HPV (human papillomavirus) and HBV (hepatitis B virus) [18,19].

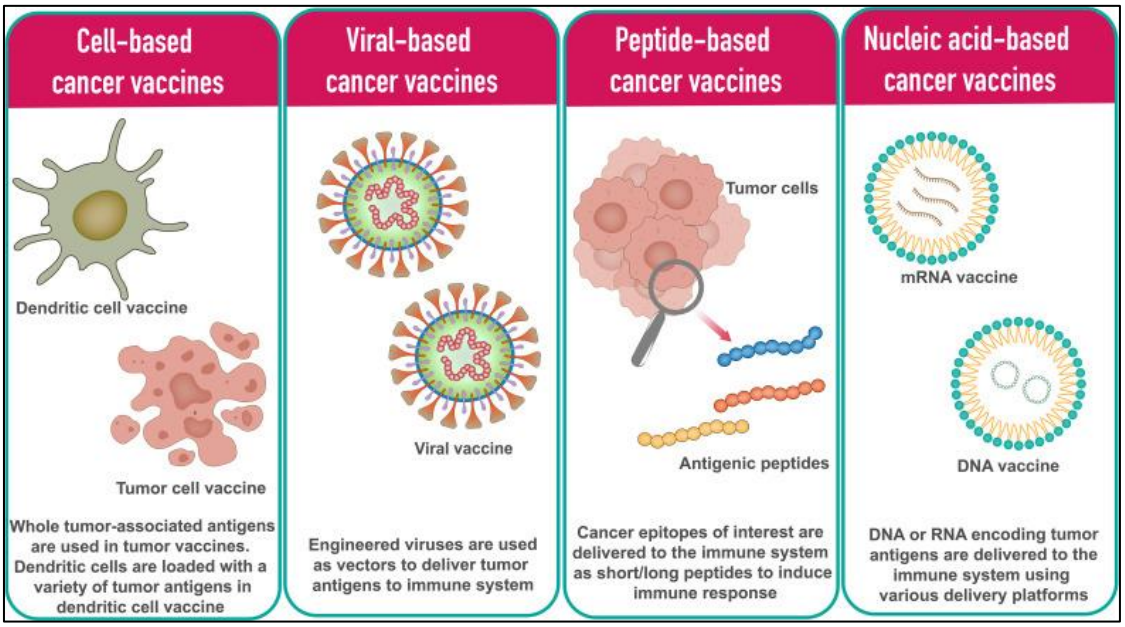

Figure 2 Different types of cancer vaccine platforms [20]

3.3. Immunoprevention: Harnessing the Immune System Before Cancer Develops

Immunoprevention refers to the use of the immune system to prevent cancer before it develops. While immunotherapy has been primarily used as a treatment for cancer, recent advancements are focusing on its use as a preventive measure [19]. One example of immunoprevention is the development of cancer vaccines that stimulate the immune system to recognize and destroy precancerous cells or viral infections that may lead to cancer. Researchers are also looking at the potential of immune checkpoint inhibitors in cancer prevention. These inhibitors work by blocking the signals that allow

cancer cells to evade the immune system. When it is used preventively, immune checkpoint inhibitors could potentially prevent the onset of cancer by strengthening the immune system's ability to detect and eliminate cancer cells before they grow into mature tumors. As a result of this, cancer survival rates are increasing in countries like the U.S. [21]. As of now, there are more preventive vaccines available than curative, including two vaccines that foster immunity against forms of the human papillomavirus that are associated with cancer development [21].

3.4. Chemoprevention: Biotechnology-Driven Approaches

Chemoprevention involves the use of natural or synthetic compounds to prevent, delay, or suppress cancer incidence using artificial or natural bioactive agents. Biotechnology has enabled the identification of a wide range of agents that can be used to reduce cancer risk. These include natural compounds like polyphenols, which are found in fruits and vegetables, as well as synthetic drugs designed to inhibit cancer-related pathways [22]. Polyphenols prevent cancer initiation through a lot of mechanisms, such as forming genotoxic molecules and blocking the activity of the mutagenic enzymes [23]. Researchers are exploring how to use selective estrogen receptor modulators (SERMs) and aromatase inhibitors to prevent breast cancer in high-risk women [24]. Biotechnology is also helping to develop more targeted chemopreventive agents that can be delivered directly to the tissues that are at a high risk of cancer. Since many biological processes, especially those related to cancer, happen at the nanoscale, nanotechnology is playing a key role in the development of advanced drug delivery systems that can enhance the effectiveness of chemoprevention. Nanovectors, which are nanoparticles, are being used to load drugs or imaging agents to prevent or treat cancer [25].

4. The Role of Artificial Intelligence and Big Data in Cancer Prevention

4.1. AI in Risk Prediction and Personalized Prevention

Artificial intelligence plays a transformative role in cancer risk prediction and prevention. By analyzing large datasets from genomics, clinical records, location, level of pollutant exposure, and lifestyle factors, AI algorithms can predict an individual's risk of developing cancer[26–29]. AI can also be used to detect early the various risk factors, such as obesity, that can predispose people to the initiation of cancers in their bodies [30]. This personalized approach to prevention can help identify high-risk individuals who may benefit from targeted screening or lifestyle interventions. For instance, AI can integrate genomic data with environmental factors such as diet, exercise, and exposure to carcinogens to provide more accurate risk assessments. This information can be used to develop personalized prevention plans, allowing for early intervention and more effective cancer prevention strategies [31].

4.2. Big Data in Cancer Prevention

Big data is being leveraged to enhance our understanding of cancer risk factors and improve prevention efforts. By analyzing vast amounts of data from population-based studies, clinical trials, and genetic databases, researchers can identify patterns and trends that could lead to more effective prevention strategies. These insights are crucial for implementing large-scale public health interventions aimed at reducing cancer mortality. Large datasets are a huge feature of genomics. The Human Genome Project generated a reference genome over 13 years at a cost of $3 billion. This genome alone contained more than 20,000 genes and over 3 billion base pairs. The possibility of sequencing every patient's genome is becoming realistic, as the NHS Genomic Medicine Service aims to make the NHS the first national health system to include whole genome sequencing in routine care [31]. Big data analytics can help identify specific environmental and lifestyle factors that contribute to cancer risk in different populations, allowing for tailored prevention strategies that address the unique needs of various communities [32,33]. By bringing together data from around the world, researchers can discover new opportunities to intervene early, helping and communicating with populations [28] that are at a higher risk of certain cancers. This collaborative approach opens doors for proactive healthcare and better outcomes.

5. Recommendations

To fully harness the potential of biotechnology in reducing cancer mortality, a strategic, multi-faceted approach is essential. While many breakthroughs in early detection and prevention have emerged recently, realizing their full benefits depends on how effectively they are implemented, accessed, and sustained across diverse healthcare systems.

First, there is a critical need to expand investment in translational research, bridging the gap between lab discoveries and real-world applications. Emergent technologies like liquid biopsy, next-generation sequencing, and CRISPR gene editing show immense promise, but many are still mostly limited to academic settings or early clinical trials [34,35]. Governments, philanthropic groups, and private investors should increase funding for research that evaluates the long-

term safety, effectiveness, and feasibility of these interventions. Longitudinal studies monitoring cancer recurrence, survival rates, and quality of life among people receiving biotech-driven preventive care.

Second, improving access and promoting equity should be a priority for any biotech-based cancer strategy. Currently, advanced diagnostics and personalized prevention benefits are mainly concentrated in high-income countries and urban areas [36]. To bridge this gap, health systems must adopt policies that make diagnostic tools like liquid biopsy panels and genetic testing more affordable and widely available in low-resource settings. Strengthening global health partnerships and technology transfer initiatives is crucial to help low- and middle-income countries build the infrastructure that is needed to implement these technologies. In addition, portable and cost-effective platforms, such as lab-on-a-chip devices, should be prioritized for development and distribution in resource-limited settings.

Furthermore, the wealth of genomic and epigenetic data offers a great chance to develop precision prevention strategies. AI-powered risk prediction models should be incorporated into routine care, especially for those with a family history of cancer or known genetic risks. These models can combine data from health records, lifestyle habits, and environmental exposures to customize preventive measures for people to follow. For instance, high-risk individuals might benefit from more frequent screenings, lifestyle counseling, or preventive therapies. Incorporating these models into electronic health systems will help clinicians to provide more personalized, proactive care.

Likewise, establishing strong regulatory frameworks for new biotechnologies is essential. Gene editing tools, especially those capable of modifying germline or inherited epigenetic markers, bring up complex ethical and safety issues [37]. Policymakers need to work closely with scientists and bioethicists to develop clear guidelines that govern the responsible use of these technologies. Addressing concerns around informed consent, data privacy, and fair access early on will be necessary, and fostering public participation in this process is also vital, as this makes sure that societal values are reflected in regulations.

Moreover, public health education and awareness campaigns are crucial for making biotechnology-based cancer prevention successful. When people are well-informed, they are more likely to participate in genetic screenings, adopt preventive behaviors, and support vaccination efforts. Education initiatives should aim to explain technologies like RNA therapeutics, cancer vaccines, and AI diagnostics. Using culturally sensitive communication strategies is essential to promote understanding and acceptance across diverse communities and to combat misinformation.

Finally, as AI and genomics become even more integral to healthcare, investment in scalable digital infrastructure is vital. Cloud platforms, electronic health records, and interconnected databases will be crucial for managing and sharing biomedical information. These digital tools will support real-time risk monitoring, improve population health management, and allow personalized interventions on a larger scale.

6. Conclusion

As the years have advanced, biotechnology has been shown to have great potential to lower cancer deaths by improving early detection and prevention. New technologies like liquid biopsy, AI-based diagnostics, gene editing, and immunoprevention are changing how we approach cancer treatment. However, making these innovations available, affordable, and practical will require harmonized efforts from researchers, healthcare providers, and policymakers. As biotechnology advances, its role in cancer prevention and early detection will only grow, potentially saving millions of lives worldwide. To fully unlock these benefits, continuous research, international collaboration, and strong public health initiatives will be necessary.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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